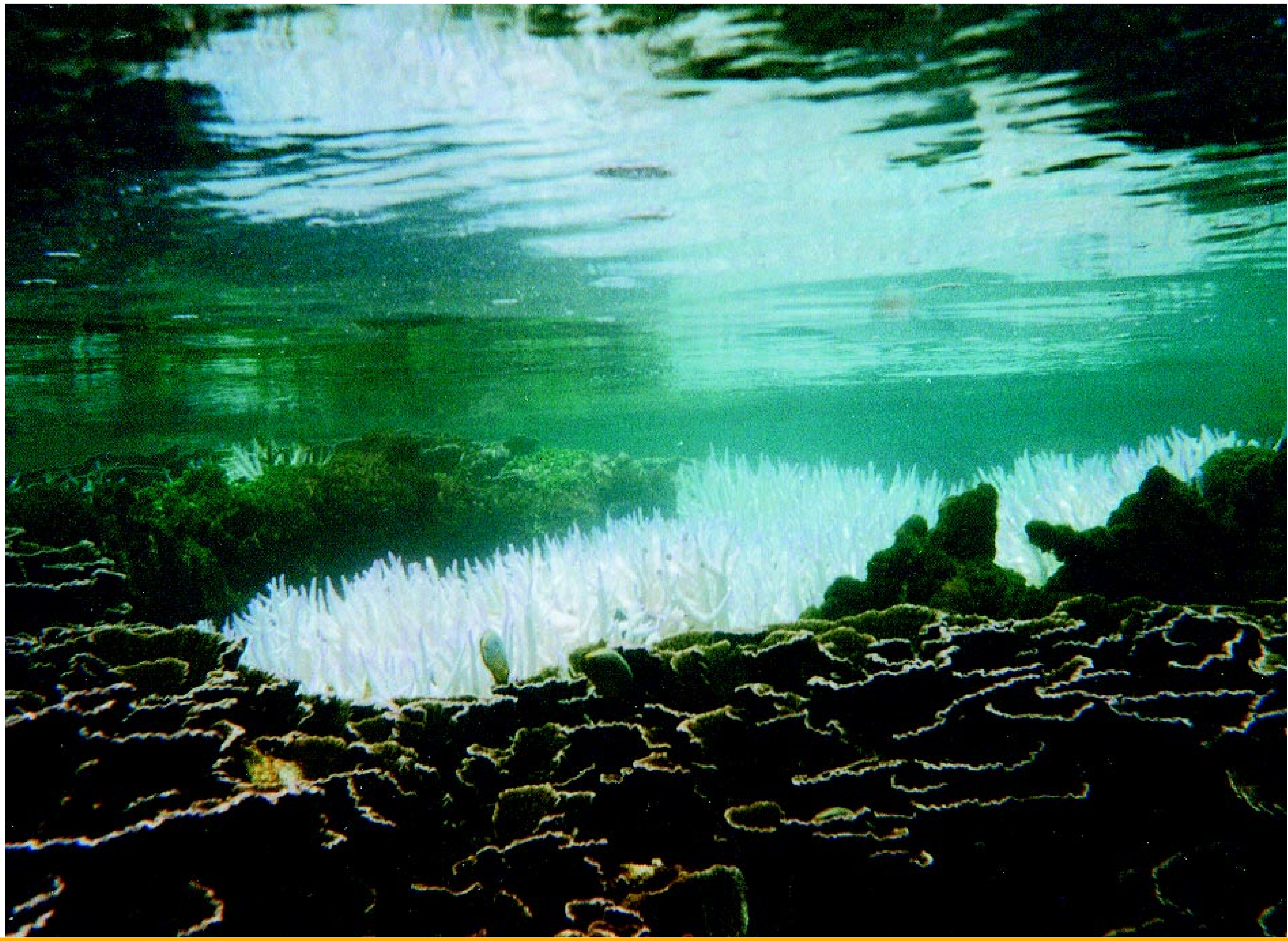
Management of Bleached and Severely Damaged Coral Reefs

Susie Westmacott, Kristian Teleki, Sue Wells and Jordan West



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General information on organizations

The Convention on Biological Diversity is an international legally-binding agreement that was opened for signature at the Earth Summit in Rio de Janeiro in 1992 and entered into force in 1993. It is the only global treaty that addresses the three levels of biological diversity: genetic resources, species and ecosystems. It is also the first to recognize that conservation of biological diversity is a common concern of humankind, that investments in conserving biodiversity will result in environmental, economic and social benefits, and that economic and social development and poverty eradication are priority tasks.

The Convention is thus a key component of the commitment by the countries of the world to implement sustainable development policies. Its triple objectives are to conserve biological diversity, to use the components of biological diversity in a sustainable way, and to share equitably the benefits arising out of the use of genetic resources.

Over 175 countries and the European Community have ratified the Convention. They have committed themselves to developing national biodiversity strategies and action plans and to integrating the conservation and sustainable use of biodiversity into decision-making across all economic sectors.

The U.S. Agency for International Development (USAID) is the U.S. government agency responsible for worldwide humanitarian and development assistance. USAID's programs foster sustainable development, provide economic assistance, build human capacity and democratic governance, and provide foreign disaster assistance. Environment programs are committed to improving conservation of significant ecosystems, reducing the threat of global climate change, and promoting sustainable natural resource management. For more information, visit http://www.usaid.gov. This publication was made possible through support provided by the Global Environment Center of USAID. The opinions expressed herein are those of the authors and do not necessarily reflect the views of USAID.

WWF, the World Wide Fund for Nature, is a large and experienced independent conservation organization, with 4.7 million supporters and a global network active in 96 countries. WWF is known as World Wildlife Fund in Canada and the United States of America.

The goals of WWF's marine conservation programme are:

- To maintain the biodiversity and ecological processes of marine and coastal ecosystems
- To ensure that any use of marine resources is both sustainable and equitable
- To restore marine and coastal ecosystems where their functioning has been impaired.

WWF has recently established the CoralWeb initiative ”Coral Reef Ecosystems in Action” in order to conserve the world's outstanding coral ecosystems and their biodiversity. CoralWeb addresses the crisis that faces coral reefs from an ecoregion perspective, and will take ecological, economic, social and policy factors into account.

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Contents

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The first draft of the text was sent to a wide audience for review and their comments have as far as possible been incorporated into this final version. Their comments were not only useful and greatly appreciated, but provided us with a broader vision for transmitting our message. Our thanks go in particular to the following reviewers: Riaz Aumeeruddy, Barbara Best, Martin Callow, Julie Church, Herman Cesar, Stephen Colwell, Helen Fox, Patty Glick, Edmund Green, Thomas Heeger, Gregor Hodgson, Irene Kamau, Olof Lindén, Tim McClanahan, Rolph Payet, Arthur Paterson, Lida Pet Soede, Rod Salm, Lothar Schillak, Charles Sheppard, Paul Siegel, Mark Spalding, Al Strong, Alan White. Our thanks also go to Jean Pascal Quod, Arjan Rajasuriya and Thomas Heeger for providing us with additional photos, Virginia Westmacott for the illustrations, Jeffrey Maganya, Amina Abdallah and the staff at IUCN-EARO and the staff at the Cambridge Coastal Research Unit who assisted with administration and logistics.

List of Acronyms

CBD	Convention on Biological Diversity
CITES	Convention on International Trade in Endangered Species of Wild Fauna and Flora
COP	Conference of the Parties
CORDIO	Coral Reef Degradation in the Indian Ocean
EIA	Environmental impact assessment
GBR	Great Barrier Reef, Australia
GCRMN	Global Coral Reef Monitoring Network
ICM	Integrated Coastal Management
ICRI	International Coral Reef Initiative
IPCC	Intergovernmental Panel on Climate Change
MPA	Marine Protected Area
NGO	Non Governmental Organisation
SBSTTA	Subsidiary Body on Scientific, Technical and Technological Advice of the CBD
SIDA/SAREC	Swedish International Development Agency Research Programme
SST	Sea Surface Temperature
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

Foreword

Coral reefs are one of the most threatened ecosystems in the world. Rivalling terrestrial rainforests in their biological diversity, and providing major economic benefits from fisheries and tourism, coral reefs ecosystems are of global concern. In addition, reefs provide many vital functions in developing countries, especially in Small Island Developing States.

Until recently, stresses caused by human activities – such as land-based sources of pollution and destructive fishing practices – were considered to be the primary dangers to coral reefs. While these problems still persist, the last two decades have seen the emergence of yet another, potentially much greater threat. Coral reefs have been affected, with increasing incidence and severity, by *coral bleaching*, a phenomenon associated with a variety of stresses, especially increased sea water temperatures. Severe and prolonged bleaching can lead to widespread coral mortality, and the unprecedented coral bleaching and mortality event in 1998 affected large areas of coral reef in the Indo-Pacific.

An Expert Consultation on Coral Bleaching convened by the Secretariat of the Convention on Biological Diversity (CBD) in 1999, recognised that there is significant evidence that climate change is a primary cause of recent bleaching events. If climate change trends continue as predicted, bleaching events will probably become more frequent and severe in the future, placing coral reefs at increasing risk.

Protection of remaining reefs, including those that have been severely damaged, is now critical if reef ecosystems are to have the maximum chance of recovery. Such protection must include removal of human impacts that can cause, aggravate or be aggravated by bleaching. Encouraging evidence from long-term studies suggests coral reefs can recover from major bleaching impacts, if additional stresses are diminished or removed. Careful management of the environment and maintenance of the best conditions possible for supporting reef recovery will be vital in the future.

The Conference of the Parties to the Convention on Biological Diversity, at its fifth meeting in May 2000, decided to integrate coral reef ecosystems into its programme of work on marine and coastal biological diversity. It also urged Parties, other Governments and relevant bodies (such as the United Nations Framework on Climate Change) to implement a range of response measures to the phenomenon of coral bleaching and physical degradation and destruction of coral reefs, including research, capacity building, community participation and education.

The World Conservation Union (IUCN) and the World-Wide Fund for Nature (WWF) are undertaking a number of initiatives relating to coral reef management, both at field sites around the world, and in the policy arena at regional and international levels. The Coral Reef Degradation in the Indian Ocean (CORDIO) programme (funded by Sweden, Finland, Netherlands and the World Bank) is one example of efforts to gather information on the biological and socio-economic implications of mass coral bleaching, and has produced valuable information, much of which is being used to develop management interventions. The U.S. Agency for International Development (USAID) is committed to helping developing nations protect their coastal areas, and recognises that the conservation and wise use of coral reef resources are critical to sustainable economic development. Towards that goal, USAID works in over 20 countries on projects that directly promote the protection of coral reef ecosystems through capacity building in integrated coastal management; strengthened management of parks and protected areas; habitat and biodiversity preservation; and sustainable tourism and fisheries.

The Secretariat of the Convention on Biological Diversity, IUCN, WWF, and USAID, in association with the International Coral Reef Initiative, decided to produce this booklet on *Management of Bleached and Severely Damaged Coral Reefs.* This joint effort is in response to the difficult question: "What can be done about coral bleaching and other damage to coral reefs?" The goal of this booklet is to provide guidance for local managers, policy-makers, and stakeholders on appropriate management approaches for coral reefs that have been severely degraded through bleaching or other causes. While scientific information is not yet adequate for precise recommendations, it is clear that the currently available knowledge must be transferred to those in positions to protect the remaining resources and stimulate recovery.

We hope that this publication will contribute to effective and immediate management action to aid reef protection and regeneration, and to enhanced research to develop the necessary tools and measures for long-term success. In addition we hope that it will be used to raise awareness of the urgent need to take all possible actions to reduce the impact of climate change on coral reefs.

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Executive Summary

This booklet was produced to provide guidance for managers, policy makers and all those who are concerned about the severe reef degradation caused by coral bleaching and a range of other impacts.

Coral bleaching is caused by high sea surface temperatures and high levels of sunlight (UV), which affect the physiology of the coral and cause a whitening effect, or 'bleaching'. This loss of colour is due to the loss of symbiotic algae (*zooxanthellae*) upon which the coral polyp depends for much of its food. Prolonged bleaching conditions (for over 10 weeks) can eventually lead to death of the coral polyp.

Sustained high water temperatures (1–2°C above normal maximums) during 1998 caused the most geographically extensive bleaching event ever recorded. The Indian Ocean was one of the worst affected regions, with coral death as high as 90% over large areas of reef. The Pacific and Caribbean regions were also affected, but they did not experience the same level of coral mortality.

Other human impacts continue to threaten the survival of coral reefs. Coastal development, poor land use practices, over exploitation of marine resources and destructive fishing methods — as well as waste disposal and pollution from ships — can all negatively affect the state of the reefs. Together, these impacts, especially when combined with increased coral bleaching, pose a serious threat to the survival of the world's coral reefs.

The Intergovernmental Panel on Climate Change (IPCC) has predicted an increase of 1–2°C in sea surface temperatures over the next 100 years, such that coral bleaching events will become a regular event in the next 30–50 years. Hence, the following types of management strategies will be crucial to safeguard coral reefs.

1. Marine Protected Areas (MPAs) will play a key role by helping to maintain sources of coral larvae to damaged areas. MPAs can also protect those areas where corals are struggling to recolonise damaged areas. Management actions in relation to MPAs, that will contribute to reef regeneration include:

- Identifying reef areas with least damage within MPAs and reviewing, and revising where necessary, zoning schemes and boundaries to ensure that healthy reefs are strictly protected.
- Ensuring that existing MPAs are effectively managed.
- Developing a more strategic approach to the establishment of MPA systems, including consideration of *sources* and *sinks* and inclusion of a wide geographic spread and variety of MPA types.

2. Reef fisheries may be negatively affected on reefs that have suffered major mortality and are losing their physical structure (and thus unable to support a diverse and abundant fish community). A precautionary approach can be taken by giving specific attention to the following:

- Establishing no-fishing zones and limitations on fishing gear to protect breeding grounds and provide fish with a refuge.
- Considering specific protection measures for species that can contribute to reef regeneration, such as algal grazers, or that might be affected by coral bleaching, such as coral-eating fishes.
- Enforcing legislation prohibiting destructive fishing practices.
- Monitoring the catch composition and size to evaluate the success of management strategies and implementing new strategies if necessary.
- Developing alternative livelihoods for fishing communities as needed.
- Limiting entry of new fishermen to a fishery through licensing schemes.
- Regulating coral collection for the curio and aquarium trades.

3. Tourism in areas with bleached reefs can be maintained through the provision of other activities, both related and unrelated to the reef. Some management options include:

- Maintaining healthy fish populations for divers and snorkellers through creative use of zoning to reduce pressure from overfishing and frequent tourist visitation.
- Involving tourists in the bleaching issue by offering opportunities for participation in monitoring programmes.
- Emphasising other attractions for tourists, both on land and in the water, besides coral reefs.
- Reducing the impacts from tourism operations in general, such as direct damage to corals from divers and snorkellers or from boat anchors, and indirect damage from coastal activities that support the tourist industry.
- Encouraging tourists to contribute financially to recovery and management efforts.
- Conveying information to the public through outreach and education.

4. Integrated coastal management (ICM) will be crucial so that bleached reefs can be managed within the context of the land-use decisions being made in adjacent drainage basins. From the perspective of coral bleaching, particular aspects of ICM that need emphasising include:

- Establishing MPA systems within an ICM framework.
- Implementing measures to promote sustainable fisheries.
- Implementing mechanisms to promote environmentally sound construction and other forms of land-use and coastal development.
- Regulating land-based sources of pollution.
- Managing shipping and other vessels to reduce damage to reefs from physical impacts or spills.
- Protecting the coastline from erosion.

5. Reef restoration is a relatively new area of research. Research should be encouraged; however, costly rehabilitation programmes may be a *risk* rather than a *cure*. Artificial rehabilitation should not be considered if human stressors continue to impact the reef. When considering restoration options, managers should consider the following questions:

- What are the ***objectives*** of the restoration project?
- What is the ***scale*** of the restoration project?
- What will be the ***cost*** of the project, and is it affordable?
- What is the ***success rate*** of the method being proposed, and which method will be most ***cost-effective*** at the site?
- What will be the ***long term viability*** of the programme?
- Is there scope for the ***local community and reef users*** to become involved?

Monitoring will enable the managers and policy makers to track changes on the reef and assess the success of management programmes. Care must be taken to design a programme that fits within the personnel and financial capacity available. In many cases, there are existing programmes that can be adopted. Meanwhile, additional research is urgently needed so we can more fully answer key questions about the ecological and socio-economic impacts of coral bleaching.

Managers can prepare for bleaching events and even aid reef recovery, but the global community needs to act now to tackle the issue of global climate change. Action at all levels from local communities and stakeholders to national governments and decision makers is required immediately to address not only the issues related to coral bleaching, but also the general state and plight of coral reefs everywhere.

Introduction

This booklet provides guidance for managers, policy makers and all those whose lives are tightly connected with the well being of coral reefs and who are deeply concerned about reef degradation caused by bleaching and a range of other impacts. Coral reefs are among the most important marine ecosystems, providing food, serving as habitat for other commercial species, supporting the tourist industry, supplying sand for beaches, and acting as barriers against wave action and coastal erosion. Ironically, the worst bleaching has taken place in countries with the least capacity and resources to address it, and with the greatest need for healthy reefs as a contribution to sustainable development. Experts are concerned that even minor declines in productivity of coral reefs as a result of bleaching could have significant social and economic consequences for local people who depend on coral reef resources, given that these people often live below the poverty line.

Fortunately, a surge in recent research is yielding new information on what the impacts of bleaching might be, both ecologically and socially. Continued research is still urgently needed so that future recommendations can be made with greater and greater precision. Meanwhile, using the information that is now available, strategic general actions can already be taken to give reefs the best chance for recovery and long-term health.

Before discussing creative solutions, we must first review the problem. The widespread coral bleaching event in the Western Indian Ocean in 1998 was especially severe in extent and degree of coral mortality. Recognising the significance of this event and the increasing global concern regarding the bleaching phenomenon, the countries that are party to the Convention on Biological Diversity (CBD) endorsed the conclusions of a specially convened Expert Consultation on coral bleaching (CBD, 1999):

- The mass coral bleaching and mortality events of 1998 appear to be the most severe and extensive ever documented.
- The geographic extent, increasing frequency and severity of mass bleaching events are likely to be a consequence of the steadily rising average of sea surface temperatures and there is sufficient evidence that climate change is a primary cause.
- The rise in sea temperature and consequent coral bleaching and mortality pose a significant threat to coral reefs and the human populations that depend on them, particularly those in Small Island Developing States.

There is, of course, no immediate *cure* for coral bleaching. However, managers and policy makers are in a position to protect remaining resources and stimulate recovery. Where bleaching has occurred, management to reduce and eliminate all forms of direct human impact that cause additional damage is increasingly important to promote conditions for reef recovery. This includes reducing pressure from over-fishing, tourism, land-based sources of pollution and development. Protection of the remaining living corals is vitally important, since these will be crucial to future reef recovery both locally and elsewhere.

Action at all levels – local, national, regional and global – is essential. Reef managers in particular need to recognise their role at the global level. For example, the area of central Indonesia that survived the bleaching may now prove critical in the recovery of many of the damaged reefs throughout the Indian Ocean, providing larvae for colonisation. Thus, actions at the local level in Indonesia could have an impact in countries and local communities hundreds or thousands of miles away.

Many global and regional initiatives are now directing their attention to bleaching and the crisis facing coral reefs. These include the International Coral Reef Initiative (ICRI) and the Global Coral Reef Monitoring Network (GCRMN), among others. The CORDIO (Coral Reef Degradation in the Indian Ocean) programme is a regional example, and the results of its work have been used extensively in developing this booklet.

The aim of this booklet is to provide a concise explanation of the causes and consequences of coral bleaching and to discuss appropriate responses. Using the 1998 bleaching

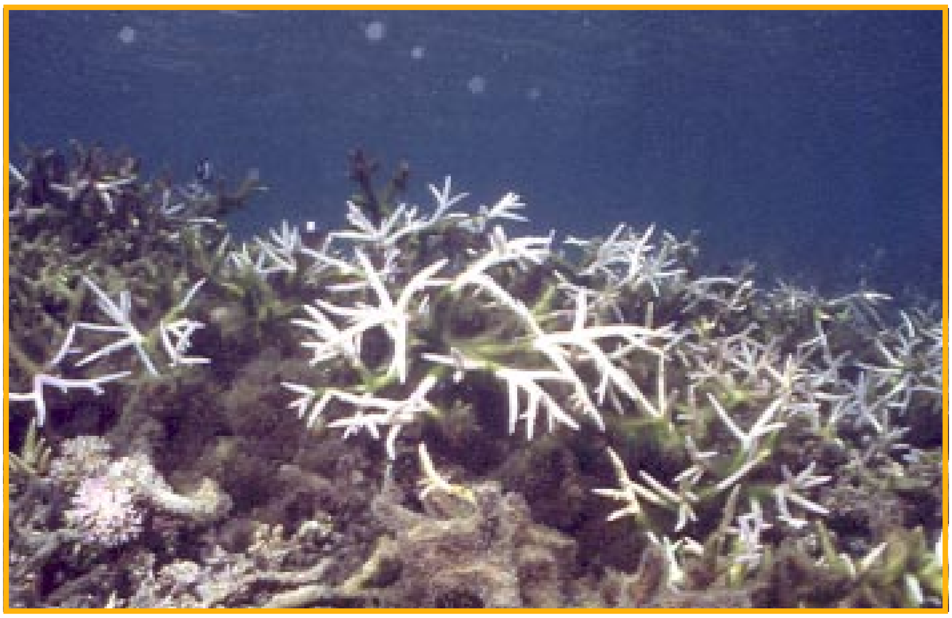


Photo: ARVAM

Bleached branching corals (*Acropora* sp.) in Mayotte, western Indian Ocean in 1998.


Photo: Susie Westmacott

Reef in the Maldives, Indian Ocean, prior to 1998 coral bleaching event.

event in the Indian Ocean as a case study, we examine this phenomenon within the context of other sources of reef degradation in order to provide guidance for managers and stakeholders. We also review the latest research and current scientific opinion on the predicted trends in and outcomes of coral bleaching. Drawing on this information, the booklet suggests precautionary measures to be taken to minimise the impact of future bleaching events and makes suggestions for positive actions that may aid reef recovery. Some of this research is still in its infancy, so careful consideration must be given to which strategies will be most effective for addressing particular issues at a given location. Managers are encouraged to make use of the information and the additional resources presented here to formulate a response appropriate to their specific circumstances.

Coral Bleaching

What is coral bleaching?

Most corals are small animals (called *polyps*) that live in colonies and form reefs. They obtain food in two ways: first, by using their tentacles to catch plankton and second, through tiny algae (called *zooxanthellae*) that live in the coral tissue. Several species of zooxanthellae may occur in one species of coral (Rowan and Knowlton, 1995; Rowan *et al.* 1997). They are generally found in large numbers in each polyp, living in *symbiosis*, providing the polyps with their colour, energy from photosynthesis and as much as 90% of their carbon requirements (Sebens, 1987). Zooxanthellae receive essential nutrients from the coral and transfer up to 95% of their photosynthetic production (energy and nutrients) to the coral (Muscatine, 1990).

In reef-building corals, the combination of photosynthesis by the algae and other physiological processes in the coral leads to the formation of the limestone (calcium carbonate) skeleton. The slow build-up of these skeletons, first into colonies, and then into a complex three-dimensional framework allows the coral reef to harbour numerous species, many of which are important to the livelihoods of coastal people and communities.

Corals 'bleach' (i.e. go pale or snowy-white) as a result of a variety of stresses, both natural and human-induced, which cause the degeneration and loss of the coloured zooxanthellae from their tissues. Under normal conditions, zooxanthellae numbers may fluctuate seasonally as corals adjust to fluctuations in the environment (Brown *et al.* 1999; Fitt *et al.* 2000). Bleaching may even be a regular feature in some areas. During a bleaching event, corals may lose 60 – 90% of their zooxanthellae, and the remaining zooxanthellae may lose 50–80% of their photosynthetic pigments (Glynn, 1996). Once the source of stress is removed, affected corals may recover, with zooxanthellae levels returning to normal, but this depends on the duration and severity of the environmental disturbance (Hoegh-Guldberg, 1999). Prolonged exposure can lead to partial or complete death of not only individual colonies but also large tracts of coral reef.

The actual mechanism of coral bleaching is poorly understood. However, it is thought that in the case of thermal stress, increased temperature disturbs the ability of the zooxanthellae to photosynthesise, and may cause the production of toxic chemicals that damage their cells (Jones *et al.* 1998; Hoegh-Guldberg and Jones, 2000). Bleaching can also occur in non-reef building organisms such as soft corals, anemones and certain species of giant clam (*Tridacna* spp.), which also have symbiotic algae in their tissues. As with corals, these organisms may also die if the conditions leading to bleaching are sufficiently severe.

The bleaching response is highly variable. Different bleaching patterns can be found between colonies of the same species, between different species on the same reef and between reefs in a region (Brown, 1997; Huppert and Stone, 1998; Spencer *et al.* 2000). The reason for this is still unknown, but the variable nature of the stress or the combination of stresses is probably responsible, along with variations in the species of zooxanthellae and densities within the colonies. Different species of zooxanthellae are able to withstand different levels of stress, and some zooxanthellae have been shown to adapt to specific coral species; this could account for variability of bleaching on a single reef (Rowan *et al.* 1997).

Bleached coral colonies, whether they die totally or partially, are much more vulnerable to algal overgrowth, disease and reef organisms that bore into the skeleton and


Photo: ARVAM

The tip of this braching coral colony (*Acropora* sp.)is bleached but alive; the lower portion has died and is now overgrown with algae.

Cross-section of a coral colony and its poylps, showing tentacles withdrawn and extended.

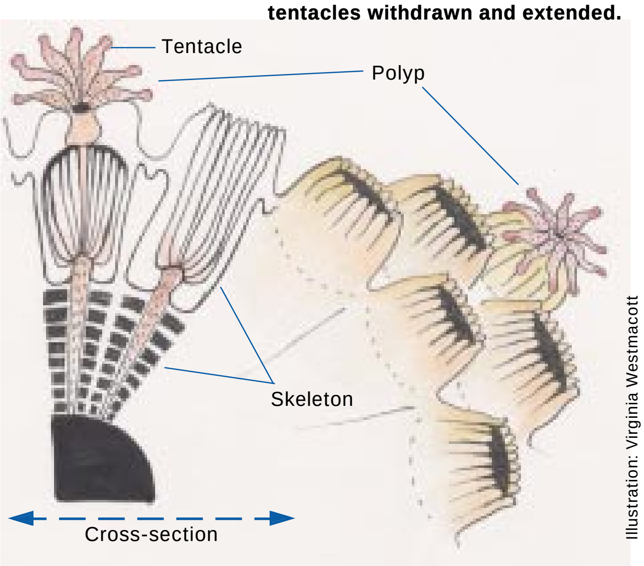


Illustration: Virginia Westmacott

Photo: Arjan Rajasuriya

Coral species differ in their responses to bleaching stressors. This photo was taken during the 1998 bleaching event: the colony on the left (*Acropora* sp.) has bleached whereas the one on the right (*Porites* sp.) has not.

Photo: Arjan Rajasuriya

Bleached branching coral colonies (*Acropora* sp.) in Sri Lanka, Indian Ocean, in 1998.

weaken the structure of the reef. As a result, if mortality is high, bleached reefs rapidly change from their snowy white appearance to one of a dull grey-brown as they become covered with algae. Where the impacts of bleaching are severe, extensive overgrowth by algae can prevent recolonisation by new corals, dramatically altering patterns of coral species diversity and causing a restructuring of the community.

What causes coral bleaching?

Stressors that cause bleaching include unusually high sea temperatures, high levels of ultraviolet light, low light conditions, high turbidity and sedimentation, disease, abnormal salinity and pollution. The majority of large-scale coral bleaching episodes over the last two decades have been linked to the presence of increased sea surface temperatures (SSTs), and in particular to *HotSpots* (Hoegh-Guldberg, 1999). A *HotSpot* is an area where SSTs have exceeded the expected yearly maximum (the highest temperature per year, averaged for a 10 year period) for that location (Goreau and Hayes, 1994). If a HotSpot of 1°C above the yearly maximum persists for 10 weeks or more, bleaching is expected (Wilkinson *et al.* 1999; NOAA, 2000). The combined effect of high SSTs and high levels of sunlight (ultraviolet wavelengths) can drive bleaching processes even faster by overcoming the coral's natural mechanisms for protecting itself from intense sunlight (Glynn, 1996; Schick *et al.* 1996; Jones *et al.* 1998).

The large scale bleaching events seen in the 1980s and early 1990s could not be fully explained by local stress factors such as poor water circulation and were soon linked to El Niño events (Glynn, 2000). The year 1983 saw the

Photo: Susie Westmacott

Colony of *Agaricia* sp. showing partial bleaching in Bonaire, Caribbean in 1998.

strongest El Niño recorded up to that time, followed by a moderate event in 1987 and another strong event in 1992 (Goreau and Hayes, 1994). Coral bleaching has also occurred in non-El Niño years, and it has been recognised that other factors besides elevated SSTs could be involved, such as wind, cloud cover and rainfall (Glynn, 1993; Brown, 1997).

Large scale bleaching episodes can usually be attributed to fluctuations in SSTs, whereas small scale bleaching is often due to direct anthropogenic stressors (e.g. pollution) that act on small, localised scales. Where both warming and direct human impacts occur together, each may exacerbate the effects of the others. If average temperatures continue to increase due to global climate change, corals will likely be subjected to more frequent and extreme bleaching events in the future. Thus, climate change may now be the single greatest threat to reefs worldwide.

Where has bleaching occurred?

Records of coral bleaching go back as far as 1870 (Glynn, 1993), but since the 1980s, bleaching events have become more frequent, widespread and severe (Goreau and Hayes, 1994; Goreau *et al.* 2000). In 1983, 1987, 1991 and 1995, bleaching was reported in all tropical areas of the Pacific and Indian Ocean as well as the Caribbean Sea.

At present, there is no standard method to quantify coral bleaching, and there has been some debate over whether inexperienced observers have overestimated the scale and severity of recent events (Glynn, 1993). Furthermore, in recent years, there have been more observers providing bleaching reports from more areas of the world than ever before (see Wilkinson, 1998). However, even during active coral research in the 1960s and 1970s, only 9 major coral bleaching events were recorded, compared to the 60 major events recorded in the 12 years from 1979 to 1990 (Glynn, 1993).

The coral bleaching event in 1998 was one of the most geographically widespread that has ever been witnessed and led to the highest level of coral death on record, especially in the Indian Ocean region. SSTs rose above coral tolerance thresholds for a longer period (more than 5 months) than had previously been recorded (Goreau *et al.* 2000; Spencer *et al.* 2000). Branching corals were the first to be affected, whereas massive corals, which initially appeared to be able to withstand the extraordinarily warm SSTs, were affected as the severe conditions continued.

Areas affected in the Indian Ocean region included large areas of reef along the coastlines of: East Africa; the Arabian Peninsula, with the exception of the northern Red Sea; the Comoros Archipelago; parts of Madagascar; the Seychelles; Southern India and Sri Lanka; the Maldives and the Chagos Archipelago. In most of these places, many corals were unable to survive the event, and coral mortality ranged from 70–99% (Linden and Sporrong, 1999; Wilkinson *et al.* 1999).

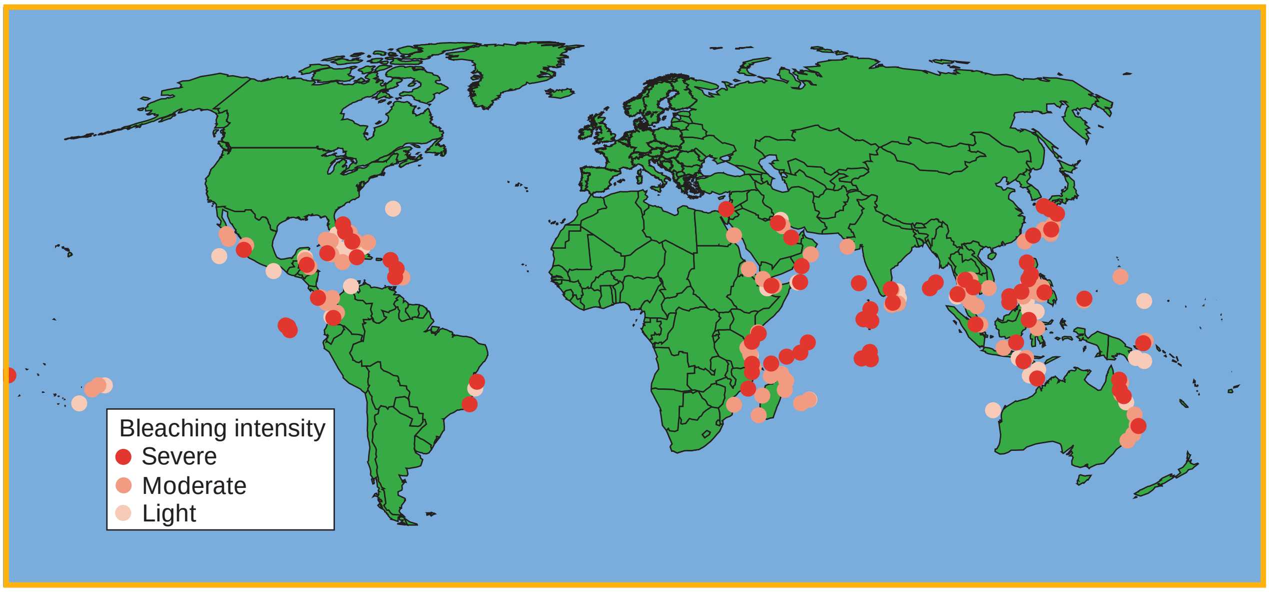
Reefs in the southern Indian Ocean around Reunion, Mauritius and South Africa were also affected although the conditions were not as severe or prolonged. Most corals eventually returned to their healthy state. This was thought to be due to monsoon conditions at the time, which caused cloud cover that reduced the levels of sunlight (and thus ultraviolet light) reaching the shallow water corals (Turner *et al.* 2000a).

The Eastern Pacific was the first area to be affected, starting in September 1997, and the conditions were the most severe this region had experienced since records of this kind have been kept; SSTs remained above the threshold for over 5 months (Goreau *et al.* 2000). Interestingly, those areas that had recovered from earlier bleaching events in 1983, 1987, 1992, 1993 and 1997, survived this recent event, while those areas that had not been previously affected were severely affected this time (Goreau *et al.* 2000).

In the Western Pacific, SSTs remained above the threshold for up to 5 months in some places. Parts of the Great Barrier Reef were bleached, with coral mortality reaching 70–80% at some sites (Goreau *et al.* 2000) while other sites had mortalities of 17% or less (Wilkinson, 1998). Some reefs in the Philippines, Papua New Guinea and Indonesia also suffered, although many central Indonesian reefs survived due to the upwelling of cooler deep waters.

Global disribution of bleaching events, 1998–2000.

(Source: World Conservation Monitoring Centre, Cambridge and United Nations Environment Programme)



In the Caribbean and Northern Atlantic, bleaching peaked during August and September 1998, with abnormally warm waters lasting 3–4 months (Goreau *et al.* 2000). Subsequent damage by hurricanes in some locations may have increased the severity of this impact (Mumby, 1999). Reports indicate that 60–80% of the colonies were affected, but in many cases, bleaching was followed by substantial recovery (Goreau *et al.* 2000).

This overview of the 1998 bleaching event underscores how variable bleaching can be in terms of geographic extent, regional severity, and even small-scale patchiness. The amount of bleaching — versus the amount of actual mortality — can also be highly variable even within a single reef system. Examples from the Caribbean and Southern Indian Ocean indicate that extensive bleaching can sometimes be followed by significant recovery. We still have much to learn about these patterns of variability and about the nature of the bleaching phenomenon. Our challenge here, however, is to use existing knowledge of coral reef ecology and best management practices to develop strategies for maximising 'successful' recoveries in the future. In order to do so, we must first consider other threats to coral reefs so they can be considered in relation to coral bleaching.

Other Threats to Coral Reefs

Bleaching from climate change is not the only threat to coral reefs. Scientists and managers have been concerned for many years that increasing stress from human activities is contributing to the decline of the world's reefs (Brown, 1987; Salvat, 1987; Wilkinson, 1993; Bryant *et al.* 1998; Hodgson, 1999). Recent estimates indicate that 10% of the world's coral reefs are already degraded beyond recovery and another 30% are likely to decline significantly within the next 20 years (Jameson *et al.* 1999). A 1998 analysis of *potential* threats to coral reefs from human activities (coastal development, overexploitation and destructive fishing practices, inland pollution and erosion and marine pollution) estimated that 27% of reefs are at high risk and a further 31% are at medium risk (Bryant *et al.* 1998). These threats are largely a result of increasing use of coastal resources by a rapidly expanding coastal population, coupled with a lack of appropriate planning and management.

Reefs that are already under stress from human activities may be more susceptible to bleaching when HotSpots develop, since weakened corals may lack the capacity to cope with the additional stress of increased sea surface temperature. Furthermore, even after SSTs return to normal, human-induced stressful conditions may inhibit the settlement and growth of new corals. Indeed, reefs that have already been exposed to persistent human disturbances often show a poor ability to recover (Brown, 1997). On the other hand, a reef that is not stressed by human activities may have a greater chance of recovery, as environmental conditions will be closer to those optimal for coral settlement and growth.

Historically, coral reefs have been able to recover from occasional natural disturbances (e.g. hurricanes, predator outbreaks, and diseases). It is the persistent, chronic disturbances from human activities that are more damaging today. This underscores the importance of removing all direct, negative human impacts that we can, to give reefs the best chance for recovery in the face of bleaching. Such impacts result from a range of activities including the following:

- Coastal development for residential, resort, hotel, industrial, port and marina development often involves land reclamation and dredging. This can increase sedimentation (which reduces light and smothers corals) and cause direct physical damage to reefs.
- Unsustainable management of adjacent drainage basins and coastal lands, including deforestation, unsound agriculture and other poor land use practices, leads to run-off of pesticides (which may poison reef organisms), fertilisers (which cause nutrient enrichment) and sediment.

Blast fishing still occurs in may parts of the world, systematically destroyig reefs.

Photo: Lida Pet-Soede

Lagoons and feef flats are destroyed in land reclamation schemes, particularly on islands where land is in short supply.

Photo: Susie Westmacott.

Badly planned hotel developments, as here in the Caribbean, often lead to erosion and damage to reefs.

Photo: Susie Westmacott.

Waste disposal and other forms of pollution are a major threat to coral reefs.

Photo: Susie Westmacott.

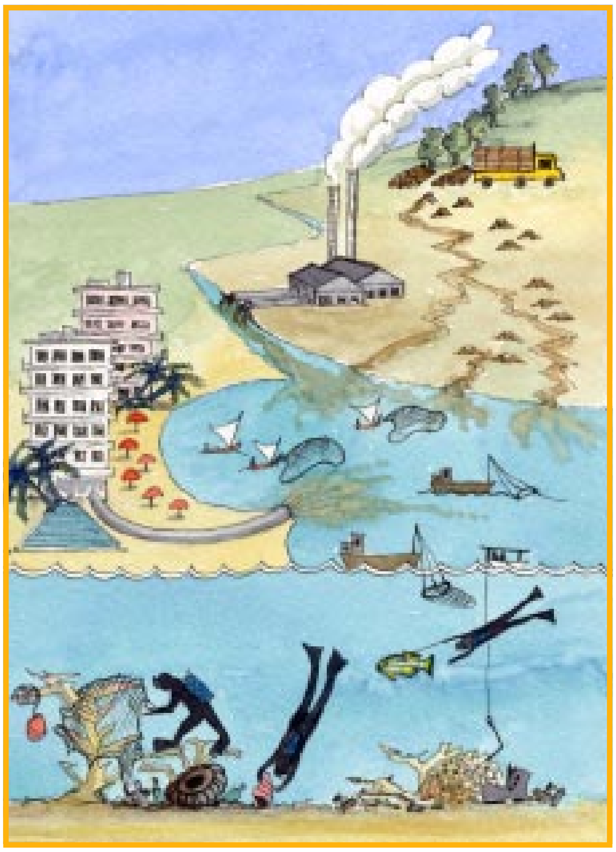


Illustration: Virginia Westmacott

The range of threats to coral reefs from human activities.

- Overexploitation can cause a number of changes on a reef. Overfishing of species that feed on algae can result in excessive algal overgrowth; overfishing of ‘keystone’ species that play a particular role in the reef ecosystem can result in population explosions of other species elsewhere in the food chain.
- Destructive fishing practices, such as dynamite fishing and the use of seine and gill nets, can cause extensive physical damage to the reef and result in the mortality of a high percentage of immature fish (i.e. the future adult fish stock). Use of cyanide and other poisons to catch aquarium fish also has a negative impact.
- Waste disposal from both industrial and municipal sources leads to increased levels of nutrients and toxins in the reef environment. Disposal of raw sewage directly into the ocean causes nutrient enrichment and algal overgrowth. Nutrient-enriched wastes from sewage or other sources are particularly damaging, as they cause a slow, gradual yet major change to the reef structure. Algae can eventually dominate the reef to the exclusion of corals (Done, 1992; Hughes, 1994).
- Ship-based activities can impact reefs through oil spills and discharge from ship ballast. Although the consequences are less well known, they may be significant locally. Direct physical damage can come from boats anchoring on the reefs and accidental ship groundings.
- Numerous other activities that take place directly on the reef cause physical damage to corals and thus affect the reef’s structural integrity. Such damage often takes minutes to occur and yet years to repair. In addition to those activities mentioned above, physical damage can be caused by trampling of corals by people collecting shells and other organisms on reef flats or in shallow reef areas, and divers or snorkellers standing on corals or knocking against the reef.

Fortunately, these are threats that managers and policy makers have the power to reduce or control. In many locations, coral reefs may be faced with several of these threats, all of which may be operating at the same time and with varying degrees of impact. Thus, it will be important to analyse carefully the situation in each location in order to set priorities and develop an effective plan of action. Managers and policy makers must identify which human impacts can be reduced most easily, and with greatest positive effect on the reef. This will involve consideration of the available capacity and financing and existing management structures, as well as analysis of the likelihood of reef recovery after bleaching or other forms of damage, both now and in the future. Thus, before we move on to discussing strategic management options, we need to consider the general outlook for coral reefs in the future.

What Does the Future Hold in Store?

Major disturbances to reefs, whether localised or global in scope, raise questions about the future of coral reefs:

- Will reefs recover after a mass mortality, and if so, when?
- What will reefs look like in the future? Will they look the same as they did before?
- What can we expect from global climate change?
- Will this disturbance happen again?

These are difficult questions, but current research is starting to provide some answers.

Coral reef resilience

Coral reef resilience is defined as the capacity of an individual colony, or a reef system (including all its inhabitants), to buffer impacts from the environment and maintain the potential for recovery and further development (Moberg and Folke, 1999). It appears that severe or prolonged negative impacts can progressively reduce resilience to subsequent impacts. This can inhibit the recovery of coral reefs following a disturbance and may lead to a shift from a coral-dominated to an algal-dominated system (Done, 1992; Hughes, 1994). Research is still underway on the resilience of reefs and their inhabitants, as even less is known about how the recovery rates of populations of species other than corals (McClanahan *et al.* in press). Meanwhile, a logical goal for managers and policy makers is to employ basic principles of sustainable use and appropriate management in order to conserve resilience. These are proactive measures to maximise a coral's, and a coral reef's, resistance to disturbance and boost resilience for maximum recovery after the disturbance has passed.

The history of disturbances on a reef contributes to its structure because reefs are naturally dynamic ecosystems. During recovery, species interact and change their levels of abundance and roles within the community structure. As a result, reefs may evolve into communities that are substantially different from those existing prior to the bleaching event, and yet still be diverse and thriving ecosystems.

The return of a coral reef ecosystem to a functional state after mass bleaching mortality will depend on successful reproduction and recolonisation by remaining corals and by corals from outside the ecosystem (see Done, 1994, 1995). Corals reproduce both sexually and asexually. Sexual reproduction involves the fertilisation of coral eggs by sperm to form free-swimming larvae. The larvae are well adapted for dispersal and, depending on species and conditions, can seed the reef where they originated, nearby reefs, or reefs hundreds of kilometres away (Richmond, 1997). Dispersal requires appropriate oceanographic currents to seed downstream reefs and is essential for the maintenance of genetic diversity amongst coral populations and coral reefs.

Recruitment is the process by which juvenile corals (known as *recruits*) undergo larval settlement and metamorphosis to become part of the adult population and

Photo: Susie Westmacott

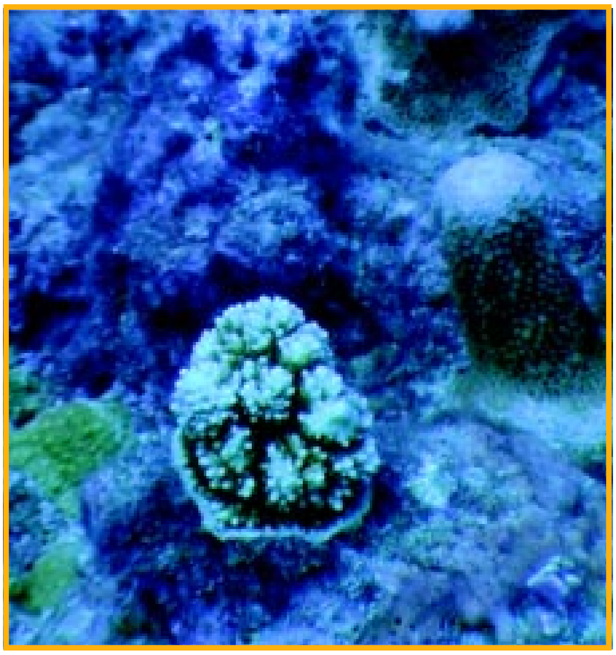


Photo: Ben Stobart

Juvenile corals growing on an area of dead coral on a damaged reef. Bonaire, Caribbean (left), Seychelles (right).

the reef community. Coral larvae settle out from the water column onto a suitable substrate; the presence of suitable substrate is critical to the success of recruitment. Good settlement sites tend to have the following characteristics (Richmond, 1997):

- A stable bottom type – the substrate must not be composed of loose sediments or unconsolidated material.
- Water motion at the site of settlement must be minimal to calm, although under certain conditions, high water motion may encourage growth.
- Salinity must generally be above 32 ‰ and below 38–40 ‰.
- A source of light for the zooxanthellae to photosynthesise.
- Limited sedimentation in the water column (ideally clear water) to reduce the chances of smothering and for the adequate transmission of light.
- An absence of macro (large) algae (as opposed to turf algae) that would compete for space with corals and inhibit the settlement of larvae.

Once settled, the coral has to compete with other faster growing organisms such as algae and encrusting invertebrates and avoid predation by coral-eating fish. The failure of reproduction (for example, if all the sexually mature corals on a reef die from bleaching) and localised recruitment will likely slow the recovery of severely damaged reefs (Richmond, 1998). However, coral cover may return eventually through asexual reproduction.

Asexual reproduction occurs when coral fragments become detached from the parent colony, usually due to physical impact from, for example, wave action or storm surge. Fragments are very vulnerable to physical damage and can easily lose their thin layer of live tissue if rolled against the bottom by water movement. However, if the fragment lands on a suitable substrate, it may re-attach itself and develop into a new colony.

A reef where the majority of the corals have died, but which has retained its structure, can still provide a stable, suitable substrate for coral recruits and fragments to settle and grow. Thus, the maintenance of dead corals is still of value. Dead corals are vulnerable to organisms that bore into them and weaken the structure of the reef. Strong waves or storm surges can cause major damage to reefs that are in this state, transforming a once complex structure into a rubble field unsuitable for coral settlement. However, red coralline algae can help to cement the reef, reducing breakage and providing an adequate substrate for the settlement of larvae.

Coral reefs have thrived under past climatic conditions, temperature, UV and current patterns.

Illustration: Virginia Westmacott

Global climate change and coral reefs

In the past 200 million years, reefs have adapted to numerous changes; however, over most of this period, there was no pressure from humans. Reefs are now faced with a combination of threats from over exploitation, pollution and especially global climate change. All of these threats are increasing, and human activities are causing the acceleration of global climate change to rates that may make it difficult for coral reefs to adapt.

Global climate change is likely to have six main impacts on coral reefs:

1. **Sea level rise**

   Most unstressed coral reefs should be able to keep up with predicted sea level rise, estimated to be 50 cm by the year 2100 (Intergovernmental Panel on Climate Change, 1995). Reef flats that are exposed at low water, which limits their upward growth, may benefit from such a rise. However, corals weakened by temperature increase or other factors (see below) may be unable to grow and build their skeletons at 'normal' rates. If so, low-lying islands will no longer be afforded the protection from wave energy and storm surges that their surrounding coral reefs currently provide. This is of major concern to nations such as the Maldives in the Indian Ocean, and Kiribati and the Marshall Islands in the Pacific Ocean, where land masses have average heights of less than three metres above sea level.

2. **Temperature increase**

   Increases of 1–2ºC in sea temperature can be expected by 2100 (Bijlsma *et al.* 1995). Many areas of the tropics have already seen an increase of 0.5ºC over the last two decades (Strong *et al.* 2000). Although these are seemingly small changes, they translate into an increased likelihood that, during the warmer periods of normal seasonal fluctuations, temperatures will exceed the tolerance levels of most coral species. This would lead to an increased frequency of bleaching (Hoegh-Guldberg, 1999). An increase in temperature may mean that areas currently outside the range of coral reefs will become suitable for coral growth, resulting in a shift in the geographic distribution of reef building populations. However, it will be some time before this can be confirmed; and should it prove true, other environmental factors at higher latitudes may not be conducive for reef growth. Furthermore, elevated SSTs affect the sensitivity of

Increased sea temperatures, storminess, carbon dioxide and UV levels, as well as changing current patterns, resulting from global warming now threaten coral reefs.

Illustration: Virginia Westmacott

zooxanthellae, such that light that is essential for photosynthesis causes damage to the cells (Hoegh-Guldberg, 1999). Corals may thus become more vulnerable to increased levels of UV radiation due to depletion of the ozone layer.

3. **Reduced calcification rates**
Global emissions of greenhouse gases have raised concentrations of carbon dioxide in the atmosphere and in the oceans to a level that may gradually reduce the ability of coral reefs to grow through normal calcification processes. High concentrations of carbon dioxide increase the acidity of the water, which reduces calcification rates of corals. It is predicted that calcification rates may be reduced by an estimated 14–30% by the year 2050 (Hoegh-Guldberg, 1999). This will reduce the capacity of reefs to recover from events such as coral bleaching as well as compromise their ability to keep pace with sea level rise and ecological shifts.

4. **Altered ocean circulation patterns**
If changes in large-scale ocean circulation patterns develop, they could alter the dispersal and transport of coral larvae (Wilkinson and Buddemeier, 1999). This could have impacts on the development and distribution of reefs worldwide.

5. **Increased frequency of severe weather events**
Alterations to annual atmospheric patterns could result in changes in the frequency and intensity of storms and cyclones, as well as changing patterns of precipitation. Increased storms could cause increased damage not only to coral reefs, but to coastal communities as well.

If trends continue as forecasted, coral bleaching will be a regular feature in 30–50 years time (Hoegh-Guldberg, 1999). Increased frequency of bleaching will force corals to adapt. Adaptation may occur in two ways:

- The physiology of corals may change to become more tolerant to higher temperatures.
- There may be mortality of populations or species of corals and zooxanthellae that are unable to cope with higher temperatures – and these less tolerant species will disappear (Warner *et al.* 1996; Hoegh-Guldberg, 1999).

Further information on potential adaptation scenarios is given in Hoegh-Guldberg (1999).

Reefs as a whole, however, are durable ecosystems, as evidenced by geological history. Major disturbances in the past have resulted in the disappearance of various coral species, but others have survived and evolved into new species. Fossilised coral structures are often visible in cliffs, sometimes far inland. Reefs have thus undergone immense changes in structure and composition over time, whilst remaining recognisable as reefs (Veron, 1995). Therefore, careful management of reefs — even those that have been severely damaged — is very worthwhile, as it could well tip the odds in favour of persistence of these long-lived systems.

Why Manage Damaged Reefs?

Managers and stakeholders are already asking questions about how to deal with bleached and damaged reefs, such as:

- What actions should they take to aid and accelerate reef recovery following bleaching related mortality events?
- How can they convince policy makers and government agencies of the value of maintaining marine parks and conservation efforts in the face of reefs degraded by the bleaching?
- Should they invest in what may be costly and risky reef rehabilitation projects?
- What socio-economic impacts will bleaching have and how can these be mitigated?
- What can be done to prepare for bleaching events in the future?

As described in previous sections, damaged reefs have the potential to recover. Coral reefs have been damaged in the past by hurricanes, storms and human activities, but they have recovered once the impact has ceased or has been reduced. This resilience has been fortunate since many people

Photo: Edmund Green

A 'healthy' reef can support a variety of reef fish – French grunts in the Turks and Caicos, Caribbean.

Box 1. Recovery following outbreaks of Crown of Thorns Starfish.

The Crown of Thorns Starfish (COTS) (*Acanthaster planci*) has devastated large areas of the Great Barrier Reef (GBR) in Australia as well as other reefs in the Pacific. The first record of a COTS outbreak (thousands to tens of thousands) dates back to the late 1950s, when large numbers of starfish were observed in the Ryukyu Islands, Japan. Not long after, in the early 1960s, outbreaks were reported on Green Island and several nearby areas of the GBR. By the time COTS outbreaks were occurring further south on the reefs off Townsville 10 years later, the northern part of the GBR was already recovering. It was feared that the structure of the Reef would be totally destroyed, exposing the North Queensland coast to increased levels of wave action and erosion. This did not happen. Whilst outbreaks of COTS may destroy some individual corals, they have not destroyed the Reef itself. During the last outbreak in the late 1970s and 1980s, starfish affected approximately 17% of the 2900 reefs that make up the GBR. Of those, only 5% of reefs were classified as having severe outbreaks.

Subsequent studies conducted on the GBR and in Guam indicated that coral cover took 12 to 15 years to return to pre-outbreak levels. Although coral cover returned after this period, the composition of the coral communities had changed, and the reefs were now comprised largely of fast growing species such as branching (e.g. *Acropora*) and plate corals. Recovery of the original species composition and diversity is expected to take much longer because the replacement of the slow growing and long lived massive corals (e.g. *Porites*) takes up to 500 years for very large individuals. However, complete recovery will eventually occur if there is no further disturbance.

Source: Bradbury and Seymour (1997), CRC Reef Research (1997) and Moran (1997)

Photo: Edmund Green

Crown of Thorns Starfish.

Box 2. Coral Reef Recovery in Kaneohe Bay, Hawaii.

Kaneohe Bay, Hawaii, is a good example of the resiliency of a reef system that has withstood persistent human impacts. It demonstrates that once the primary source of disturbance is reduced, recovery is possible. Increased soil erosion, sedimentation, reef dredging, canalisation of streams and sewage discharges occurred from the 1940s through the 1970s. A range of impacts, including freshwater flooding and run-off from erosion and human-influenced land use changes, damaged the bay's coral reefs.

After twenty-five years of discharge, two large sewage outfalls were diverted from the bay in 1977 and 1978. There was a corresponding change from a seabed dominated by a green 'bubble alga' (*Dictyosphaeria cavernosa)* and filter- or deposit-feeders, to a habitat more closely approaching the 'coral gardens' described by earlier visitors. Coral cover more than doubled in the following 15 years. Although recovery has since slowed, the story of Kaneohe Bay illustrates how well a reef can recover once the anthropogenic stress is reduced.

Source: Hunter and Evans (1995)

depend on reefs for their livelihoods. The economy of the Maldives, for example, has traditionally been based on fisheries and tourism, both of which are linked directly to the reefs, which have been severely affected by bleaching. Thus, there are good reasons for continuing management efforts in order to:

- Ensure optimal conditions for reef recovery.
- Ensure sustainable reef fisheries.
- Ensure the continuation of the tourism industry.

Reef recovery will vary from reef to reef according to the unique set of circumstances at each location. Under suitable conditions, reefs may well be able to return to thriving, diverse communities, providing direct benefits in terms of fisheries, tourism and recreation and indirect benefits, such as coastal protection and scientific research (see Box 1).

Careful management can help, either by reducing negative impacts, as occurred at Kaneohe Bay in Hawaii (see Box 2), or by improving conditions for recovery. Recovery will only take place if additional stresses from human activity can be limited. Optimal conditions for maximising reef ecosystem recovery include:

- A solid, submerged surface free from algae on which coral larvae can settle and grow; when corals die during a bleaching event, the rock they leave behind is potential substrate for new recruits.
- An area free of overfishing, sedimentation, pollutants, fertilisers, untreated sewage and any other inputs that will hinder the growth and affect the survival of coral recruits; good water quality and the lessening of physical impacts will facilitate coral recruitment and growth.
- The existence of sexually mature corals in the area to provide new larvae; the ability of unaffected reefs, far away from an impacted reef, to provide larvae will depend on suitable ocean currents and the health of the source reefs. Any remaining local corals will also be an invaluable source of larvae for the area.
- Protection from over-fishing in order to maintain a healthy fish population; herbivorous fish will graze on the fleshy algae and keep the dead coral available as substrate for coral colonisation.

These conditions can be maximised through careful planning and management. Using the background information that we have reviewed thus far, we are now ready to discuss reef conservation strategies in the context of marine protected areas, fisheries, tourism, and integrated coastal management.

Marine Protected Areas and Damaged Reefs

Despite the mortality that has followed some bleaching events, particularly that of 1998, there has never been total elimination of all living corals in any area. Even in the severest cases, scattered colonies and small patches of reef have survived. Furthermore, new coral recruits are often observed within a year after the event. This provides a starting point for reef recovery and a hope for the future.

The role of marine protected areas

Marine protected areas (MPAs) may play an increasingly important role in reef conservation and management in the future by:

- Protecting areas of undamaged reef that will be sources of larvae, and thus instrumental in assisting recovery.
- Protecting areas that have a lower vulnerability to future HotSpots due to, for example, cold water upwelling.
- Protecting areas that are free from anthropogenic impact and have suitable substrate for coral settlement and re-growth.
- Ensuring that reefs continue to sustain the needs of local communities that depend on them.

Areas in which corals have managed to survive a warm water event will be of key importance for the supply of coral larvae to replenish degraded areas. Reefs that have the potential to supply larvae are often known as *source* reefs, in contrast to reefs that receive larvae via ocean currents and are sometimes referred to as *sink* reefs. Some reefs may be *sinks* at one time of year and *sources* at another time, where monsoonal currents reverse in different seasons.

Source reefs need to be 'upstream' from damaged reefs if ocean currents are to play a role in larval transport and reef recovery. Pockets of live coral on a damaged reef may also act as sources of coral larvae. These corals may have survived because they are: on the deeper reef where water temperatures varied less; in lagoons, where they may be used to large daily fluctuations in temperature; or protected by specific oceanographic phenomena, such as the upwelling of cool deep waters. These potential sources of larvae need to be identified, managed appropriately and protected from further damage, particularly where this is human-induced, in order to promote recovery and boost the resilience of individual coral colonies and the reef system as a whole.

Several factors determine whether a reef is a good source of coral larvae:

- The presence of large coral colonies that may produce large numbers of larvae.
- High coral diversity, which may increase the chance of rapid colonisation by opportunistic, fast growing species and later by slower growing species.
- Minimal presence of human impacts on the reef, such that the chance of coral reproduction and larval survival is maximised.
- Presence of upwelling water, which will assist with the transportation and survival of coral larvae.
- The presence of prevailing wind and oceanic currents that flow past the source reef and towards the degraded (sink) reef.

Management actions

1. **Identify reef areas with the least damage and review zoning schemes and boundaries.**
   Surveys of reefs within MPAs should be carried out as a matter of urgency, to identify those that are healthy and that might contribute to recovery of the overall area. Where these sites are inadequately protected, consideration should be given to revising the zoning scheme and/or the overall boundary of the MPA. It may be necessary to create new zones or alter the boundary of the MPA, provided that the legislation allows for this. It may also be necessary to create entirely new protected areas for healthy reefs that are not currently within MPAs, at least temporarily while surrounding degraded areas are recovering. Thus, a flexible approach to zoning and regulations will be needed over the recovery period.

2. **Ensure that MPAs are effectively managed.**
   Damaged reefs within MPAs are likely to recover faster if they are well managed and not subjected to additional stresses such as heavy tourist visitation. A number of guidelines and management handbooks are available to assist with this (e.g. Kelleher, 1999; Salm and Clark, 2000). Training courses for MPA managers are also now widely available, and capacity building programmes are being developed in many areas (e.g. the Western Indian Ocean (Francis *et al.* 1999). Community involvement

Areas of live coral will act as a source of larvae for areas affected by the bleaching.

Illustration: Virginia Westmecott

Photo: Susie Westmacott.

Ste Anne Marine Park in the Seychelles is one of many marine protected areas to have suffered from the 1998 bleaching event.

Box 3. Effect of coral bleaching on Marine Protected Areas in the Seychelles.

Coral bleaching had a severe impact on MPAs in the Seychelles, and live coral cover was reduced to less than 10% on most reefs around the inner islands (Turner *et al.* 2000b). Funding for management of the park currently depends entirely on visitor entrance fees and, if visitor numbers fall, income to the Marine Parks Authority will decline.

Visitors to Ste Anne Marine Park and Curieuse Marine Park have been declining in number since 1996 (i.e. since before the bleaching event). The Marine Parks Authority is now looking for new attractions for visitors, in order to ensure sufficient income to maintain the parks. Visitor centres are being planned, breeding pens for giant Aldabra tortoises are being constructed and picnic areas are being improved. In addition, terrestrial activities in the MPAs – such as nature trails and bird watching activities – are being expanded. Some recovery of the reefs is occurring, but effective management of the parks will be essential to this continuing process.

Source: Westmacott and Lawton (2000)

will greatly increase the effectiveness and success of the management of MPAs (Walters *et al.* 1998), as will the incorporation of MPAs into an integrated coastal management (ICM) framework. MPA managers should be involved in ICM planning and implementation, to promote the needs of coral reefs and to encourage the creation of conditions that will lead to reef recovery. Damaged coral reefs affect visitor numbers to an MPA, as well as the livelihoods of those who depend on the MPA for employment, such as naturalists, guides, and park staff (see Box 3). If the MPA is dependent on visitors for revenue, this aspect of management will need to be reviewed and the potential for promotion of attractions other than coral reefs, assessed.

3. **Develop a more strategic approach to the establishment of MPA systems.**

For the development of national and regional MPA systems, a more strategic approach may be required to take into account *source* and *sink* reefs and the dispersal patterns of coral larvae. Research into current patterns of larval dispersal will be useful; however, unfavourable current patterns for long distance dispersal should not preclude the establishment of a protected area, which will still act as a *source* reef for its own renewal and for localised dispersal (Roberts, 1998). Because the dispersal of coral larvae occurs across national and political boundaries, regional and international co-operation will be essential. The issue of 'transboundary' larval dispersal is as important as transboundary issues of marine pollution and fisheries, both of which are covered by regional and international agreements.

Another important strategic consideration is the concept of 'bet-hedging' against the probability of bleaching by establishing systems that cover a wide geographic spread and a wide variety of reef types. If an MPA system includes a full geographic spread, then the odds will be good that at least some well-protected healthy reefs will survive if HotSpots should develop unpredictably throughout the region. For the same reason, it is also very important for MPA systems to include all types of habitats across the reef profile (i.e. reef flats, reef slopes, lagoons, lagoon channels).

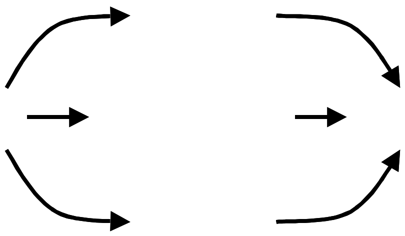
Fisheries and Coral Bleaching

Coral reefs support a wide range of valuable fisheries, including both fish and invertebrate species. Utilisation by humans may occur on a large commercial scale or on a small artisanal scale. The primary purpose of some fisheries may be the harvest of food, while other fisheries may involve the collection of merchandise for the curio and aquarium trades. All of these enterprises could potentially be affected by coral bleaching. While most fisheries research to date has focused on edible fish, we can nevertheless use current theory to deduce the potential impacts of bleaching and reef degradation on reef fisheries in general. After a review of basic fisheries theory, we will employ the precautionary principle to make some general recommendations.

The impact of coral bleaching on a fishery may follow the generally accepted theories on habitat-fish interactions on coral reefs (Pet-Soede, 2000). Apart from exploitation itself, several factors contribute to the composition of fish communities on a reef, all of which are related to the physical structure and complexity of the reef itself.

First, competition for food is one important factor determining fish diversity and abundance. On a healthy reef, diversity and abundance of food is high and this has a direct positive effect on fish diversity and abundance (Robertson and Gaines, 1997). On a degraded reef, dead coral is soon overgrown with algae which are eaten by herbivores such as parrotfish (*Scarus* spp.), and the population of such species may increase. Heavy grazing by these species sometimes damages the reef structure, causing erosion of the coral skeletons, but they also keep algal growth in check. Also, the increase in populations of these commercially valuable fish can be an economic benefit.

The links between reef health and fish diversity and abundance.



Second, the reef provides a suitable environment for reproductive activities and larval settlement of fishes, and these will in turn determine the adult community structure (Medley *et al.* 1983; Eckert, 1987; Lewis, 1999). A healthy complex reef structure will maximise the variety and numbers of spaces for successful reproduction.

Finally, the reef provides shelter and protection from predators, particularly for small fish species, and this affects their survival patterns and abundance as adults (Eggleston, 1995). Overall, reef health has a positive effect on all three of these factors (food, reproduction and shelter), and these in turn enhance fish diversity and abundance.

How fisheries could change on damaged reefs

Current research suggests that coral bleaching has no immediate effect on fish catches (Box 4). This is partly due to the fact that reef fish communities are slow to respond to environmental change, and partly because few fisheries depend on a single stretch of coral reef. Coral mortality following bleaching will, however, eventually affect a fishery as the reef structure degrades, and there are a number of possible outcomes (Pet-Soede, 2000):

- Where there is no coral death, whether bleaching has been localised or is extensive, it is unlikely that there will be any change in the fishery, either in catch composition or catch rates.
- Where bleaching is localised and coral mortality is low, there could be localised changes in reef fish community structure, particularly if specific coral species are affected. The resulting decline in coral diversity and habitat complexity could affect the composition of local catch and catch rates.
- Where bleaching is extensive and results in mass coral mortality, there could be significant changes in the fishery, with longer-term changes related to the loss of habitat complexity and diversity through erosion of the dead coral. Species that feed on corals, such as butterflyfish, and those that specifically use corals for shelter, such as some damselfish, would be expected to decline first. However, there have already been reports suggesting that the first changes may be in the abundance of algal grazers such as parrotfish and surgeonfish, as a result of

Live coral (left) provides a suitable habitat for a diverse and abundant fish community unlike a degraded reef (right).

Illustration: Virginia Westmacott

Photo: Kristian Teleki

In Kenya, dhows are typical fishing vessels for local fishermen whose livelihoods depends on the health of the reefs.

Box 4. The impact of bleaching on reef fisheries in Kenya.

Since the 1998 bleaching event, there has been little significant effect on the catch biomass and composition of reef fisheries in both MPAs and non-protected areas in Kenya. The gradual decline in total fish abundance that has been seen since monitoring began in 1995 is due to other human-induced impacts and has not been accelerated by bleaching and coral mortality. One possible exception is the increase in Surgeonfish which was observed in some MPAs. This was probably a short term response to the increase in algal cover. However, the effect of the bleaching event may only become evident once increased erosion and loss of three-dimensional reef structure occurs, which would be expected to take place in the next two to 10 years. Indeed, at the time of writing, observations were suggesting that Surgeonfish populations were already declining.

Source: McClanahan and Pet-Soede (2000)

algae overgrowing dead corals (Goreau *et al.* 2000; McClanahan and Pet-Soede, 2000) (see Box 4).

- An additional potential impact, as yet unconfirmed, is that coral bleaching could lead to an increase in ciguatera poisoning. Ciguatera toxins are produced by microscopic single-celled algae (dinoflagellates) that grow especially well on the surface of larger, fleshy reef algae. When fish graze on the algae, the toxins can become concentrated in their bodies and cause poisoning in humans. The phenomenon appears to be linked to disturbance of coral reef ecosystems, perhaps due to increased overgrowth by large algae (which provide more surface area for dinoflagellate growth) on degraded reefs (UNEP, 1999a; Quod *et al.* 2000).

Changes to a reef as a result of coral mortality could affect the fish yield, the type of fishery, and the spatial distribution of the fishing effort:

- Maximum yields may be reduced through a reduction in food and suitable environment for fish reproduction and shelter. The consequences of this may vary according to the type of fishery:
  - In a fishery that is entirely dependent on reef fish, catch rates may decrease, and the catch composition may shift towards the herbivorous species. These fish are often lower in market value, which could lead to a reduction in income for the fishers. Fishing communities with few alternative sources of income may have difficulty sustaining their livelihoods.
  - A fishery that targets large free-swimming fish that forage for food near reefs may also experience lower catches if those species move to other less damaged areas to hunt for prey.
  - A fishery that targets smaller free-swimming species that occupy a reef area or lagoon during certain phases in their life stage may also experience lower catches when reefs disappear.
  - Multi-species and multi-gear fisheries, which are common in the Indian Ocean and other reef areas, are probably flexible enough to adapt to changes in fish stocks and their resource base. The relatively long period over which changes in fish stocks occur facilitates adaptation.
- Changes in the reef structure could encourage the use of damaging fishing methods, such as trawling, that were previously excluded because of the damage the reef would do to the gear.
- Spatial changes in the reef habitat characteristics may require fisheries to move their fishing effort to other areas for certain target species.

Local communities dependent on reef fisheries, such as this fish drying enterprise in the Seychelles, may need to seek alternative livelihoods if damaged reefs affect their source of income.

Management actions

Even in the absence of bleaching, sustainable management of fisheries is a challenging task, as large numbers of people are involved, many with no other sources of income or protein. Many local communities will have few alternative livelihoods and little potential for adaptation to these new conditions. Increasing understanding, co-operation and a feeling of ownership in local communities will be critically important. While uncertainty exists about the actual effects of coral bleaching on fisheries, a precautionary approach can be taken by giving specific attention to the following actions:

1. **Establish no-fishing zones and limitations on fishing gear** to protect breeding grounds and provide fish with a refuge.
2. **Consider specific protection measures for:**
   - Algal grazers, such as parrotfish and surgeonfish, that are likely to play a key role in maintaining suitable substrate for coral larvae settlement.
   - Coral-eating fish, such as butterfly fish and damselfish collected for the aquarium trade, that may be diminishing in number because their preferred habitat and source of food is decreasing.

   Consideration could be given to implementing a moratorium on the collection of some of these species on reefs badly damaged by bleaching, until such time as recovery of the reef is well underway.
3. **Enforce legislation prohibiting destructive fishing practices** (e.g. dynamite fishing, gill and seine netting, use of cyanide and other poisons) that would further damage the reefs.
4. **Monitor the catch composition and size** to evaluate the success of management strategies and implement new strategies if necessary.
5. **Develop alternative livelihoods for fishing communities as needed.**
6. **Limit entry of new fishermen to a fishery through licensing schemes.**
7. **Regulate the collection of coral reef organisms for the curio and aquarium trades.** Legislation regulating these activities exists in many countries and should be enforced. CITES (Convention on International Trade in Endangered Species of Wild Fauna and Flora) helps to control international trade by requiring permits for the export of all stony corals and some shells (e.g. giant clams). Countries that Parties to CITES should implement their obligations.

Tourism and Coral Bleaching

Diving and snorkelling come immediately to mind as reef-related tourism, but reef areas are also valuable for beach tourism, cruise ships, yachting, fishing and other water sports. With the changes to coral reefs that might be brought about by coral bleaching, there is justified concern by those dependent on the tourism industry and by managers of MPAs:

- How will tourists react to bleached reefs?
- How can the tourism industry adapt to the problem of bleaching?
- How can tourism be managed to reduce further damage to bleached reefs?

The 1998 bleaching event has thus far not had much impact on tourism (Westmacott *et al.* 2000a). Indeed, dive operators have reported that tourists were still enjoying the reefs even at the height of the event – and some actually commented on what they perceived to be 'clean' corals. The true impact of bleaching on tourist visitation may in fact not be seen for several years, and may only come once the reefs are seriously degraded. Nevertheless, work in the Indian Ocean suggests there may be some future impact from the 1998 event (see Box 5).

Tourists may react in various ways to bleached and damaged reefs. If they are aware of bleaching (from the media, through word of mouth, or other sources of information), they might choose not to visit the affected area, in which case the tourism industry will suffer at all levels. The most experienced divers and snorkellers are likely to notice changes on the reefs – particularly the change from bright colours to a rather dull uniform grey or brown. Some will visit once but then cease to return as they might have done in the past. Those new to these sports may not be aware of any problems. These people, as well as those not interested in direct reef-related activities, may continue to visit an affected area. Alternatively, tourists might still visit the area, but not the reefs themselves, in which case only the diving and snorkelling industries will suffer.

Management actions

1. **Maintaining healthy fish populations for divers and snorkellers.**
   Diverse and colourful fishes are one of the main attractions for divers and snorkellers, and a degraded reef may eventually see a decline in overall fish numbers. Methods for addressing this problem are described in the section on *Fisheries and Coral Bleaching*. In relation to tourism, these actions include:
   - Reducing fishing pressure from around dive and snorkel sites.
   - Establishing no fishing zones in which diving and snorkelling are permitted.
   - Zoning separate areas for diving and snorkelling versus fishing, to reduce conflicts.
   - Banning destructive fishing practices that lower fish populations and destroy interesting underwater features.

2. **Involving tourists in the bleaching issue.**
   Many divers and snorkellers like to get involved in conservation activities for coral reefs and would welcome the opportunity to participate in initiatives associated with reef recovery from bleaching. Fish watching schemes and amateur reef monitoring programmes are increasing, such as the US-based REEF (Reef Environmental Education Foundation) and CEDAM (Conservation, Education, Diving, Awareness and Marine-research) organisations and a number of others that operate

Box 5. The impact of coral bleaching on tourism in the Indian Ocean.

Surveys undertaken in the Indian Ocean in 1999, one year after the bleaching event, suggest that bleaching had a smaller impact on tourism than expected. The level of concern among tourists about bleaching seemed to be related to their country of origin and the level of publicity afforded to this event in that country.

In Zanzibar, 28% of the divers interviewed had heard of bleaching, compared to 45% in Mombasa, Kenya. Although the reefs in both locations were bleached, only slight coral mortality was seen in Zanzibar, compared to over 50% coral mortality on some reefs in the Mombasa region. Less than 5% of divers and snorkellers interviewed in both places said that they would not dive or snorkel because of bleaching. Based on the number of tourists who said their activities would be affected, a potential financial loss of US$13–20 million in Mombasa and US$3–5 million in Zanzibar has been estimated. Time will tell whether this is a realistic estimation.

In the Maldives, 48% of tourists interviewed said that the most disappointing part of their holiday was the dead coral. However, tourist arrivals have continued to increase, with an 8% growth rate during 1998 and 1999, compared to 7% during 1996 and 1997. Continued growth in tourist arrivals in the Maldives is partially due to other types of tourists having replaced divers. Even before the bleaching occurred, the Maldives was already taking active steps to encourage tourism by promoting the islands as a destination for couples on honeymoon. This would imply that the bleaching has, as yet, not had an effect on the tourism industry. However, as a result of the increase in hotel bed capacity in 1997, a 10% growth in tourist arrivals for the period between 1998 and 1999 was forecast. If coral bleaching was in fact the cause of the growth rate being only 8%, rather than 10%, it could be calculated that bleaching resulted in an estimated financial loss of US$ 3 million.

Source: Cesar *et al.* (2000) and Westmacott *et al.* (2000b)

In the Maldives, where diving ia a major source of income to local people, the tourist industry is taking a major role in assisting with reef management.

Photo: Susie Westmacott

internationally (e.g. Coral Cay Conservation, Frontier, Raleigh, Earthwatch, Reef Check). In the Bonaire Marine Park, Netherlands Antilles, for example, there are yearly visits from both REEF and CEDAM, and those visits form an integral part of the Park's monitoring programme (see sections on *Monitoring and Research* and *References and Resource Materials*).

3. **Diversifying the tourism industry.**
   In order to monitor changes in tourist visitation to reefs, regular surveys should be carried out, for example, in airport departure lounges where tourists wait for their flights. Several countries already carry out such surveys through the government department responsible for tourism. Survey questions can be specific to diving and snorkelling and other directly reef-related activities, or they can cover broader tourism activities. Monitoring changes in the tourism market will indicate whether marketing of alternative tourism activities is required to maintain the industry. For example, terrestrial based tourist activities could be the focus while damaged reefs are given a chance to recover; however, care must be taken to ensure that coastal development for such activities does not itself cause additional damage to

Clean, beautiful beaches will help to maintain tourism in areas where reefs have been damaged.

Photo: Kristian Teleki

reefs. Much greater attention may need to be paid to the landscape value of an area, clean beaches, clear waters for water sports, etc. It may be necessary to seek new or alternative dive sites (e.g. with dramatic underwater scenery or populations of large fish).

4. **Reducing impacts from tourism operations in general.** Where reefs have been bleached and degraded, the management of the surrounding tourism activities is essential. The following impacts, among others, should therefore be reduced or eliminated (see also sections on *Other Threats to Reefs, Marine Protected Areas, Fisheries* and *Integrated Coastal Management*):

- Direct contact from diving and snorkelling (by walking on or knocking into the reefs); providing information to divers and educating them about the potential damage they can cause may be sufficient to eliminate damage. In addition, offering divers free buoyancy workshops may also help to improve their buoyancy control underwater, and making glove-wearing illegal also inhibits intentional touching of reef organisms.
- Over use of a reef or dive site; relocating dive sites or limiting numbers of divers at popular dive sites can reduce damage to reef areas that are in the process of recovering.
- Physical damage from boat anchoring; anchoring of boats (dive, fishing, pleasure craft, etc.) – can be managed by designating anchorage zones, providing alternatives, such as moorings, and enforcing other regulations relating to environmentally sound anchoring.
- Near shore contamination from waste disposal (e.g. sewage from resorts); it may be appropriate for coastal resorts to treat wastewater on site or to use it in the maintenance of their gardens so that excess nutrients will be used by the plants.
- Sedimentation and pollution from construction (e.g. piers and jetties, harbours and marinas); guidelines are available for many construction and engineering activities, and methods have been developed to reduce their impact. These can be promoted and implemented by making them conditions of the approval for planning or of the Environmental Impact Assessment, through legislation and permit systems, and through incentive measures.

5. **Encouraging tourists to contribute financially to recovery and management efforts.** Managing coral reefs, whether they are healthy or recovering from damage, requires adequate financial resources that are often lacking in the countries worst affected. The tourism industry, which in many areas is dependent on or makes extensive use of coral reefs, should contribute to the costs of management. Individual divers and tourists can assist through payment of park entrance and other fees or by making donations. As Box 6 shows, tourists are often willing to contribute

Mooring buoys prevent damage to reefs from boat anchors.

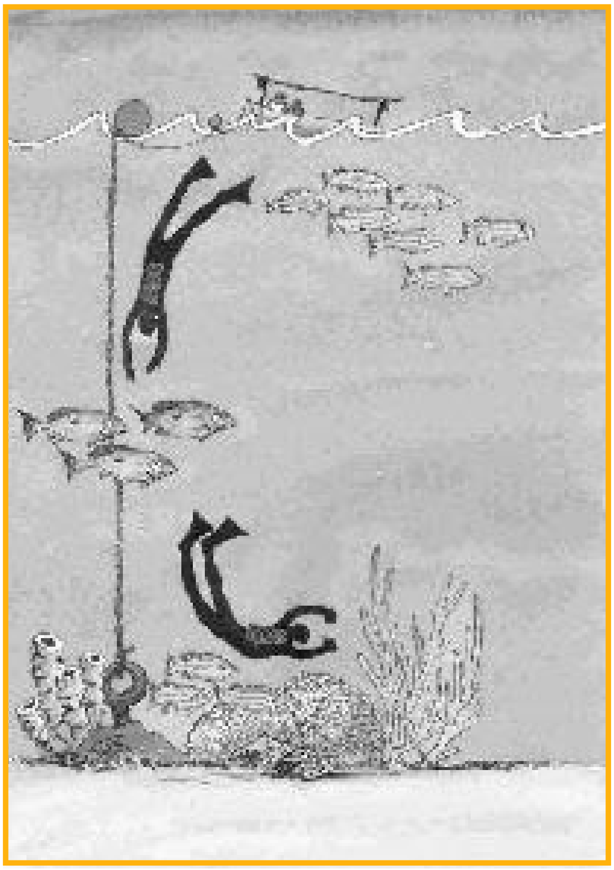


Illustration: Virginia Westmacott

Box 6. Asking divers to pay for reef conservation.

Divers show considerable 'willingness to pay' for good quality reefs. In the Maldives, a survey following the bleaching event of 1998 showed that each tourist would be willing to pay an additional US$87 on top of their actual holiday cost to be able to visit healthy rather than degraded reefs. Since around 400,000 tourists visit the Maldives a year, this would translate to a total of US$19 million during 1998 and 1999 (Cesar *et al.* 2000).

Similar surveys in Zanzibar in 1996 (before the bleaching) and 1999 (after the bleaching) showed a willingness to contribute towards reef management of US$22 per diver in 1999 compared to US$30 in 1996. This change could be related to not only the decline in reef quality (a 20% decrease in hard coral cover from November 1997 to November 1998 at certain sites (Muhando, 1999)), but also to other factors such as the type of tourist visiting this country. The only difference between the divers interviewed in 1996 and 1999 was that the former were less experienced divers; their income and other socio-economic variables were comparable which suggests that the difference in willingness to pay could be related to either reef quality and/or to their level of experience. In Mombasa, divers were on average willing to contribute US$43 to maintain reef quality, their level of experience was generally higher than those interviewed in Zanzibar, and they made many more dives. These factors could account for their willingness to pay more than divers in Zanzibar.

Source: Westmacott *et al.* (2000b)

substantial sums if they are assured that the money will be used for reef conservation. The socio-economic profile of the visiting tourist, as well as the quality of the reefs and other attractions, will be important factors when assessing how much tourists might pay for reef management activities. Thus, surveys should be carried out in each area to determine these factors before user fees are introduced.

6. Conveying information to the public through outreach and education.

The tourism industry can play an important role in education and outreach activities. These might include:

- Fact sheets on the "dos and don'ts" of enjoying coral reefs and on the relationship between climate change and coral bleaching, which can be included in the information packets that hotels provide to their guests.
- Colourful and informative posters that can be sold in local tourist shops or park offices.
- Training courses for tourist operators on how to educate tourists on reef biology and threats to reefs.
- Free boat tours of MPAs and slide show lectures for members of the community, especially those who deal extensively with visiting tourists, so that they will feel a sense of stewardship toward their reefs and will help to educate tourists that they meet.

Integrated Coastal Management and Coral Bleaching

Coral reefs, particularly fringing reefs, are often found close to the coast and may lie just metres from the shoreline. Rapid population growth and increasing demand for industry, tourism, housing, harbours and ports are resulting in extensive coastal development. As mentioned earlier, these have a major impact on coral reefs and, as with other human activities, are likely to impede recovery of reefs that are affected by bleaching. The health of adjacent ecosystems, such as seagrass beds and mangroves, also has an important bearing on the health of coral reefs. Furthermore, maintaining the aesthetic value of the coast, including clean beaches and water, and unspoiled landscapes, will become increasingly important if coral reefs themselves become less attractive to tourists. Addressing these issues will require careful attention to planning and regulation of coastal development and waste disposal, and may best be addressed by integrated coastal management (ICM).

ICM considers the coastal zone and its associated watershed as a single unit and attempts to integrate the management of all relevant sectors (Bijlsma *et al.* 1993; Post and Lundin, 1996; Cicin-Sain and Knecht, 1995). Many countries have initiated or are implementing ICM programmes at local and/or national levels. Belize, for example, has found this a particularly useful framework for addressing threats to coral reefs (Box 7). In Tanzania (another country where coral reefs are vital resources that have also been affected by bleaching), a national ICM policy is under development, and local site-specific ICM programmes are being implemented to

Box 7. Managing the Belize Barrier Reef through an ICM approach.

Belize has one of the most extensive reef ecosystems in the Western Hemisphere, comprising one of the largest barrier reefs in the world, three atolls and a complex network of inshore reefs. These have been affected by several of the recent bleaching events although, in general, the country benefits from some of the most healthy reefs in the Caribbean. The Great Barrier Reef Marine Park in Australia was viewed as a potential model for management of the country's reefs and associated ecosystems. However, the need for management of land-based activities was recognised as fundamental, and the ICM approach was adopted as a general framework.

The ICM programme has been underway since 1990, and an institutional structure has been established to co-ordinate management activities in the coastal zone. Measures laid out under the national Coastal Zone Management Plan are of direct benefit to reefs and include: a zoning scheme for the coastal zone, incorporating MPAs; fisheries management measures; a national mooring buoy programme; legislation and policy guidelines; policies to address offshore industries and shipping; research and monitoring programmes; education and public awareness campaigns; measures for community participation; and a financial sustainability mechanism.

Source: Gibson *et al.* 1998

Replanting mangroves can build up the coast's natural protection against erosion and reduce sedimentation onto nearby reefs as seen here in Mauritius.

Photo: Susie Westmacott.

Photo: Susie Westmacott.

Integrated coastal management involves careful planning and zoning of construction and other activities, such as the location of jetties to avoid erosion.

test planning and co-ordination mechanisms on the ground (Francis *et al.* 2000). The states of the Western Indian Ocean have shown particular political commitment to the establishment of ICM programmes through a number of Ministerial level meetings (Lindén and Lundin, 1997).

This booklet has covered MPAs, fisheries and tourism in separate sections, all of which are vitally important elements of a successful ICM programme. Other issues include:

- Land-based sources of pollution.
- Construction and other activities in coastal areas and along watersheds.
- Agriculture, forestry and other land-use practices in coastal areas and along watersheds.
- Offshore mining and oil and gas industries.
- Activities related to vessels and all forms of shipping.

It is not possible here to discuss every issue that an effective ICM programme should address, but it is valuable to note that they are all important for successful coral reef management and to create the conditions that will maximise recovery of damaged reef ecosystems.

Expensive sea defence structures are frequently used to prevent erosion, but promoting the recovery of reefs as natural breakwaters may be a better long-term strategy.

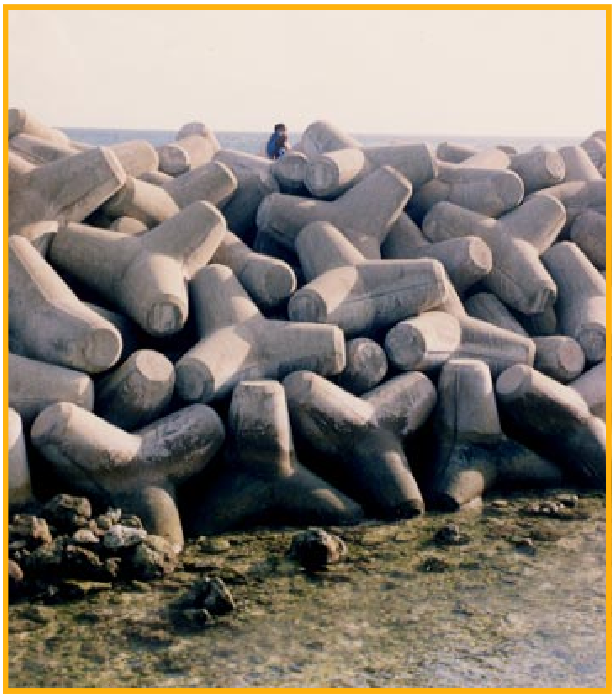


Photo: Susie Westmacott.

Management actions

The primary need is to continue the development and implementation of ICM policies and programmes at both national and local levels. Successful ICM requires recognition of the principles of: stakeholder participation and promotion of co-operation among user groups; the precautionary principle; and monitoring and evaluation of management interventions to ensure that these are adapted in response to changes in ecosystem health (this is particularly important in the case of vulnerable ecosystems such as coral reefs).

Guidance on ICM is available from many sources (e.g. Clark, 1996; Post and Lundin, 1996; Ehler *et al.* 1997; Hatziolos, 1997; Cicin-Sain and Knetch, 1998; WWF/IUCN, 1998). ICM policies and programmes, however, need to pay greater attention to creating conditions for reef recovery and to maintenance of the health of those reefs that are as yet undamaged. Therefore, the following actions need emphasising:

1. **Establishment of MPA systems within an ICM framework** that take into account what is known about the inter-connectedness, vulnerability and resilience of different coral reefs.
2. **Implementation of measures to promote sustainable fisheries management** and integration of these within the overall economic development of coastal regions.
3. **Development and implementation of planning tools, guidelines, legislation, incentive measures** and other mechanisms to promote environmentally sound construction and other forms of land-use and coastal development.
4. **Regulation of land-based sources of pollution.** Pollution of this nature has to be addressed at international, regional, national and local levels, and many initiatives are underway. Reef managers and policy-makers can help to promote new technologies and endorse innovative methods for sound waste disposal, such as the use of wetlands to filter out nutrient-rich wastes, and 'dry' or composting toilets.
5. **Management of shipping and other vessels to reduce damage to reefs and associated ecosystems from groundings, anchoring, spills and waste disposal.** As with land-based sources of pollution, this is a topic that cannot be covered

in full here, and managers and decision makers are referred to the sources of information given at the end of this booklet. A good legal framework for regulation of commercial shipping now exists, as a result of the efforts of the International Maritime Organisation. However, not all countries have the domestic legislation, resources or capacity to develop and implement the necessary measures. These include contingency and rapid response planning for oil spills, regulations on dumping, provision of port facilities for waste disposal, appropriate routing and navigation schemes or the designation of vulnerable areas (such as coral reefs) with special regulations for shipping (e.g. Particularly Sensitive Sea Areas, or PSSAs). Regulation of the activities of smaller vessels is also essential. Managers should promote the establishment of mooring buoys, development of codes of conduct for boat operators and training of boat operators in safety and environmentally sound operational practices.

6. **Protection of the coastline from erosion.** Coastal erosion may increase if reefs, which previously provided protection from waves and storms, are damaged. Erosion of several metres of beach has been reported in some areas of the Seychelles where reefs were affected by bleaching (Souter *et al.* 1999). This may lead to the introduction of expensive engineering solutions that will not always stop the erosion. Allowing the land to adapt to the changes through natural processes ('soft' engineering) may be a better approach, as well as promoting the recovery of damaged reefs (see section on *Restoration Techniques*) to recreate their natural breakwater function.

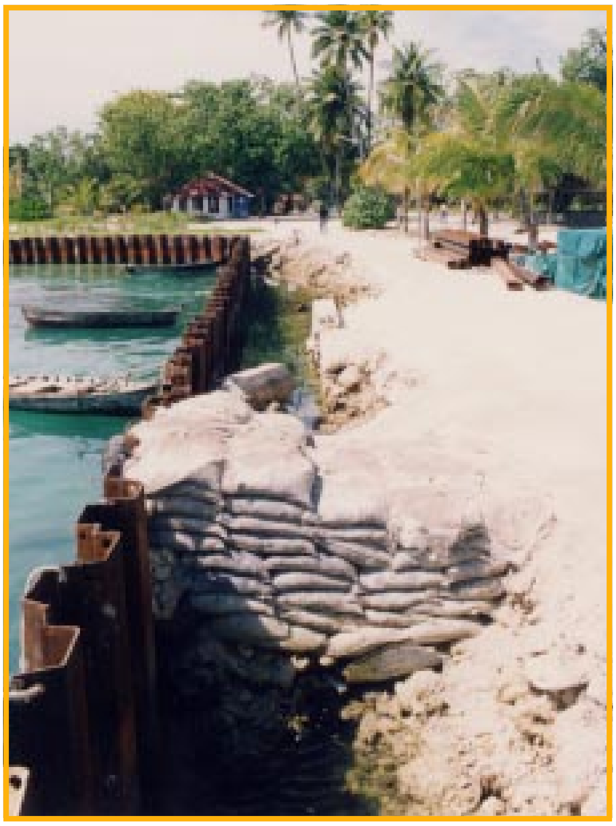


Photo: Susie Westmacott.

Sedimentation can be reduced during harbour construction by using revetments, as here in the Maldives.

Restoration Techniques

Restoration techniques can be used to aid and speed recovery of damaged reefs by enhancing or supplementing natural processes of resilience. However, it is essential to look at the scale involved when considering whether to restore reefs affected by bleaching mortality. Many rehabilitation efforts have not proved effective or feasible on a large scale (km^2), either economically or ecologically. There is also little point in carrying out costly restoration if the damaging impacts are present. Furthermore, natural recovery processes may already be at work and may be interrupted by restoration activities, which in such cases would be more harmful than beneficial. Very careful assessment must therefore be made to determine whether active intervention is advantageous. Natural recovery in many instances may be better than risky, costly 'cures'.

Thus far, most active coral reef restoration and rehabilitation techniques (e.g. those described below) have been attempted only in localised areas and on a very small scale (less than 100 m^2). Such methods are unlikely to alter more than a tiny area of reef and will have minimal overall impact on reefs, even in small countries. They, however, may have value in sites such as small 'coral gardens' that have very high value in terms of tourist visitation.

A number of different approaches are being researched at present:

Removing stresses

This should always be the first priority, as it will encourage natural recovery processes. Methods for improving conditions for coral growth through the removal of existing and potential stresses that inhibit the settlement, survivorship and growth of corals are described in earlier sections.

Increasing available substrate for larval settlement

Although after a bleaching event, dead coral provides a surface for larval settlement, the availability of suitable substrate can rapidly decrease due to algal overgrowth. For this reason, it is important that land based sources of pollution causing nutrient enrichment are minimised and algae-eating fish populations are maintained. Increasing available substrate for larval settlement is only necessary once the reef structure has been degraded. Solutions for increasing substrate availability range from simple to complex, and from cheap to expensive. Most of these are still being studied:

- Various researchers are testing the practice of placing artificial substrates on the seabed, such as concrete blocks (Clark and Edwards (1999) – see Box 8), wrecks (Wilhelminson *et al.* 1998) or other structures (Rilov and Benayahu, 1998; ReefBall, 2000). Such *artificial reefs* may have an additional benefit of providing a refuge for reef fish (Whitmarsh, 1997). Care should be taken to avoid any pollution or further damage to the surrounding environment as a result of the materials selected or the design of the structure. For example, scrap metal or other junk should not be used, even though it may appear to be an easy waste disposal solution (van Treek and Schuhmacher, 2000). The cost of installing artificial reefs or large areas of artificial substrate is likely to be prohibitive for large expanses of degraded reef.
- Consideration is being given to stabilising or removing loose substrate material (such as coral fragments) and removing algae (McClanahan *et al.* 1999) and other organisms that might inhibit larval settlement or damage young recruits.
- The use of electrolysis to deposit a calcium-based material on to an artificial surface is at a very experimental stage. Electrical currents cause calcium and magnesium minerals to precipitate from the seawater onto a conductive material, such as chicken wire. The resulting framework consists mainly of calcium carbonate, and is similar to reef limestone (Hilbertz *et al.* 1977). Proponents are testing this for natural settlement of coral larvae and for transplantation of corals (see below) (e.g. Hilbertz, 1981; van Treeck and Schuhmacher, 1998, 1999; Schillak and Meyer, 1999; Meyer and Shillak, 1999). This technology may be applicable on a small scale to stimulate coral growth on small patches of reef but because of the high initial costs involved, it may not be feasible on a large scale.

Transplanting corals from one area to another

Corals can be removed from a reef and transplanted, either to natural substrate on a damaged reef (Lindahl, 1998), or to artificial substrates such as concrete blocks (Clark and Edwards, 1999). This tends to be an expensive method (unless volunteer labour is readily available for the transplantation work) and often has a low success rate, as transplanted corals tend to be more vulnerable to stress (see Edwards and Clark, 2000). The source of corals for transplantation must also be

Box 8. Reef Rehabilitation in the Maldives.

Corals have been a major source of construction materials in the Maldives for many years, and reefs adjacent to the capital, Male, have been virtually denuded. In an experimental study, concrete blocks were placed on these damaged reefs to evaluate different restoration techniques.

Natural recovery processes were remarkably efficient. Within six months, coral larvae had settled on the blocks and within one year, densities of 31 recruits per m^2 were recorded. Corals were also transplanted onto the blocks from nearby reefs, but this resulted in considerable mortality, with survivorship only about 50% after two years. It appeared that where suitable surfaces for settlement were available and water quality was conducive to coral growth, natural recruitment could result in substantial restoration of the reef within 3–4 years — without the need for transplantation.

Source: Clark and Edwards (1999)

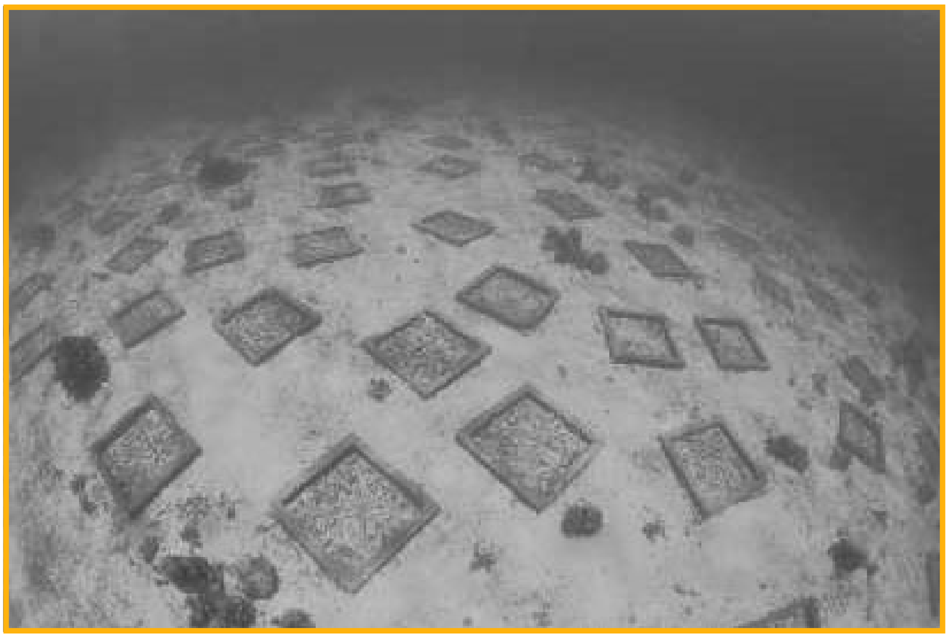


Photo: Thomas Heeger

Coral farm on Olango Island, Philippines: the small enclosures shelter the transplanted coral fragments.

Women from the local village prepare coral fragments for transplanting into enclosures.


Photo: Thomas Heeger

Box 9. Coral farming in the Philippines.

In 1997, a low-cost coral farm with the primary aim of reef rehabilitation was set up with the assistance of the village people in Barangay Caw-oy, Olango Island, Cebu, Philippines. Six thousand fragments were cut from corals on nearby reefs and transplanted to a reef with low coral cover. After 4 months, 87% of the coral fragments had survived, and fish populations on the farm are reported to have increased. The farm is also providing a livelihood to local people through the sale of coral colonies for rehabilitation of damaged reefs in other areas of the Philippines. The profits are used for community projects such as scholarships, first aid rooms and street lighting.

The cost of rehabilitating one hectare of reef, using 2 fragments per square-metre (12.5% cover) was US$ 2,100. Since, the potential revenue from one hectare of a healthy reef in the Philippines has conservatively been estimated at US$ 319 – 1,113 a year (White and Cruz-Trinidad, 1998), using this method, reef rehabilitation would be potentially economically viable after a few years. This would be especially true if local fishermen find better livelihood alternatives in coral farming and shift from destructive fishing techniques.

Source: Heeger *et al.* (1999, 2000)

chosen with care, to avoid damage to other reefs. The best source is probably those reefs that are certain to suffer major damage in the future from dredging, land reclamation, effluent discharge or activities that cannot be stopped or for which there is no mitigation.

Farming corals

Several attempts have been made to farm corals, mainly in Southeast Asia (see Box 9) (Franklin *et al.* 1998). Unlike straight coral transplantation, in the case of 'coral farms', the fragments are transplanted to a protected site and 'grown out' to a certain size before being used for other purposes. Successful coral farms could provide a source of corals for rehabilitating damaged reefs and could be used as underwater attractions for snorkellers (Alcock, 1999). Further investigation into coral farming is required to reduce costs and increase success rates. Studies in Australia have shown that mortality rates may be as low as 2–5% and that the removal of up to 50% of the biomass of a 'donor' coral colony may have no effect on its growth (Alcock, 1999).

Management actions

Since active reef restoration is generally expensive and not always successful, managers must assess the situation carefully before initiating such a programme and consider a number of factors:

1. What are the ***objectives*** of the restoration project? Are the reefs being restored for biodiversity conservation, tourism, fishing, protection from coastal erosion or purely for research? The objectives will help to determine the methods to be used.
2. What is the ***scale*** of the restoration project? Is the degraded area a specific location (i.e. anchor scar or boat grounding), a section of the reef or an entire reef complex? If the degraded area is large (e.g. following a major bleaching event), careful thought must be given as to where restoration efforts should be directed in terms of current patterns (encouraging downstream coral seeding but avoiding upstream sources of pollution) and exposure to potentially damaging wave action, sources of pollution and turbidity.
3. Once the objectives and scale have been considered, the ***cost*** of the project needs to be evaluated, taking into account the most effective use of any available funds (see Spurgeon (1998) for more details).
4. What is the ***success rate*** of the method being proposed? Which method will be most ***cost-effective*** at the site? It is important that the method selected does not cause additional injury to the reef.
5. What will be the ***long-term viability*** of the programme? To ensure some measure of success, the project should continue long enough for the restoration progress to be monitored.
6. Is there scope for the ***local community and reef users*** to become involved? Active participation by those whose livelihoods are linked to the reefs will increase the chances of success (see Box 9).

Monitoring and Research

Monitoring

A well-designed monitoring programme is a very important tool for tracking changes on bleached reefs and for monitoring the general condition of those still unaffected. Monitoring should start simply, be adaptive and flexible, and be designed to meet management goals. Local organisations, universities and non-governmental organisations (NGOs) can carry out some of the best monitoring. These groups have the flexibility to design their monitoring programmes within their own capacity and are able to work with local people, which is an important factor in determining the long-term sustainability of monitoring programmes. There are also now a number of regional and global reef monitoring programmes available with accompanying guidelines, handbooks and training activities. Reef managers can also access some of the global temperature monitoring programmes, such as that underway through NOAA. The two principal global programmes both pay particular attention to bleaching:

- **Global Coral Reef Monitoring Network (GCRMN)**
  The GCRMN focuses on government level (or professional) monitoring. Once fully in place, the global network will consist of fifteen independent regional networks, or sub-nodes, in six regions around the world.

Photo: ARVAM

Coral cover being assessed after bleaching using a line transect.

Photo: Erik Meesters

Left: New coral growth, such as recruits, being measured with a quadrat.

  Via these regional networks, the GCRMN promotes sound scientific methods for monitoring and assists with the provision of training. For example, two nodes have been established in the Indian Ocean – one in Sri Lanka, servicing the countries of South Asia, and one in Mauritius, covering the island nations of the Western Indian Ocean. The data collected are stored in regional databases and used in national reports on reef status. The national results are collated into *Status of the Reefs* reports that will be published every two years; the first status report was produced in 1998 (Wilkinson, 1998). GCRMN is currently developing a manual for assessing socio-economic parameters relevant to coral reefs, which will be very useful in the context of coral bleaching.

- **Reef Check**
  Reef Check is a protocol for rapid assessment of reefs, and is specifically designed for non-professionals and volunteers. Initiated in 1997, it is carried out annually on a worldwide basis and now involves a large pool of enthusiastic volunteer SCUBA divers and free divers in over 40 countries. A network of regional, national and local co-ordinators match up teams of experienced recreational divers with professional marine scientists. The scientists are responsible for training, leading the surveys and ensuring accurate data collection. The Reef Check methods employ carefully selected indicator organisms based on those advocated by the GCRMN. The methodology can be learned in one day and involves a strict quality control system. Thus, Reef Check represents the 'community-based' monitoring protocol of the GCRMN. Further information is available in Hodgson (1999, 2000) and on the Reef Check website (see *References and Resource Materials* section).

There are a number of key issues to consider when developing a monitoring programme in relation to bleaching or other serious damage on reefs:

1. What regional or national monitoring programmes are available in the area? These should be contacted through web sites or directly through the programme co-ordinators (see *References and Resource Materials* section). Reef Check's methods are available on their web site, and GCRMN outlines its protocol online. Both may be able to facilitate funding or initial support. Other organisations or programmes in a region may also be able to provide assistance.
2. What are the objectives of the monitoring programme? These should be clearly defined, as they will influence the methods selected. The methods themselves should be simple, but flexible and adaptive, so that as resources become available, more detailed information can be collected, or more sophisticated methods used.
3. The first step should be a rapid assessment of the bleached or damaged area, the results of which can then be compared to any available pre-impact data.
4. Biological, physical and socio-economic data should be collected, so that recovery can be related to the broader environmental and social context. Biological data describe ecosystem health and might include coral cover and diversity, fish abundance and seagrass density.

Physical data should include measurements of temperature, turbidity, sedimentation and nutrients. Socio-economic data include a wide range of parameters, such as number of fishermen and catch, visitation levels and diver numbers, income levels, employment rates and sewage disposal. Particular care must be taken in selecting methods for socio-economic monitoring, and it is important to seek advice on this important component of a monitoring programme.

5. The monitoring methods selected must suit the available financial and human resources and must not require skills beyond the capacity of the available personnel. A simplified level of monitoring that is reliable and accurate is better than either no monitoring or a complex programme that exceeds the organisation's capacity and results in unreliable data. In most cases, highly trained personnel are not necessary to collect the basic information needed to track changes due to bleaching.
6. The selection of monitoring sites must take into account the management strategies being used in protected and non-protected areas, and whether such sites should be on so-called *source* and *sink* reefs.
7. Adequate time must be allowed in work programmes for both the data collection and data analysis. The data collected should be compared with any previously collected data, and should be contributed to regional and global monitoring programmes as appropriate.

In many countries, lack of capacity within a management agency is a major constraint to setting up monitoring programmes. Several of the global and regional programmes organise training courses as required and may be able to provide funding. Reef managers should nevertheless look at other ways of acquiring the same information. These might include:

- Recruiting people from local communities, such as fishermen and dive operators. For example, the NGO Reef Care in the Netherlands Antilles has used local communities to monitor the spread of a sea squirt (*Trididemnum solidum*), a pest on the reefs of Curaçao and Bonaire (van Veghel, 1993, Bak *et al.* 1996).
- Using volunteers, either trained scientists or recreational divers; these can provide additional monitoring capacity at very low cost, although the latter may not be able to provide the same level of accuracy, reliability and detail as the former. Careful selection of volunteers and of the methods they are to use is essential (Wells, 1995). Volunteer programmes are better than no monitoring at all, and when carefully designed and tested, they can provide managers with reliable and accurate data for effective management. Examples include Coral Cay Conservation (Mumby *et al.* 1996), Frontier (Darwall and Dulvey, 1996), and REEF (Schmitt and Sullivan, 1996) (see *References and Resource Materials* section for contact details).

Research

We still have much to learn about the coral bleaching phenomenon and its potential impacts on both coral reefs and the people who depend on them. Reef managers and policy makers can encourage scientists, marine laboratories, non-governmental organisations and government agencies to perform studies that address gaps in our knowledge of coral bleaching. In order to predict (and mitigate) the impacts of coral bleaching, we will need a better understanding of:

- The biology of coral bleaching, including the physiology of the coral/zooxanthellae symbiosis and how it is disrupted when bleaching occurs.
- The genetic factors that may determine the vulnerability of certain species of corals and zooxanthellae to bleaching.
- The spatial and temporal patterns of bleaching, and the climatological and oceanographic factors that determine such patterns.
- The potential for recovery of corals and coral reef ecosystems after bleaching.
- The role of coral reefs as a critical habitat for a variety of marine species and natural resources.
- The current status of coral reef health and other threats to coral reefs.
- The socio-economic implications of coral bleaching for human communities that depend on their coral reefs for a variety of natural services.

As with all research, bleaching-related work should be carefully planned to maximise scarce resources and to use methods appropriate to the objectives of the study. When possible, research programmes should be designed in collaboration with reef managers and other stakeholders, and local and national expertise should be used. Regional research programmes may be able to provide financial and technical assistance.

Addressing Global Climate Change – the Ultimate Challenge

The suggestions made in this booklet will help managers to prepare for bleaching events or aid reef recovery after bleaching and other impacts have occurred; however, the problem of coral bleaching will become increasingly severe if accelerated global warming continues. According to the Intergovernmental Panel on Climate Change (IPCC), average SSTs in the tropics are expected to increase by about 1–2°C over the next 100 years (Watson *et al.* 1996). The bleaching event of 1998 has already shown that coral reef conservation can no longer be achieved without consideration of the global climate system.

In 1998, the 4th Conference of the Parties to the Convention on Biological Diversity (CBD) expressed its deep concern at the extensive and severe coral bleaching event and its possible relationship to global climate change. In response, the Executive Secretary of the CBD convened an Expert Consultation on Coral Bleaching in October 1999. The Experts produced a report and a set of recommendations on priority areas for action. This report was presented to the CBD's Subsidiary Body on Scientific, Technical and Technological Advice (SBSTTA-5), which further expanded on the proposed actions. The SBSTTA then forwarded their suggestions to the 5th Conference of the Parties to the CBD (COP-5), which (in May 2000) endorsed the Expert's recommendations and passed a decision to:

- Integrate coral reefs into the marine and coastal living resources element of their programme of work.
- Urge Parties, other Governments, and relevant bodies to develop case studies on coral bleaching and to implement response measures including research programmes, capacity building, community participation and education.
- Implement a specific work plan on coral reef conservation in cooperation with organisations such as the United Nations Framework Convention on Climate Change (UNFCCC), the Intergovernmental Panel on Climate Change (IPCC), the International Coral Reef Initiative (ICRI), and the Global Coral Reef Monitoring Network (GCRMN) and other international bodies.
- Urge the UNFCCC to take all possible actions to reduce the effect of climate change and to address the socio-economic impacts on the countries most affected by coral bleaching.


Photo: Edmund Green

Healthy and diverse reef in the Turks and Caicos, Caribbean.

There is a clear link between the coral bleaching issue and the stated objectives of the UNFCCC. Article 2 of the UNFCCC explicitly acknowledges the importance of natural ecosystems and urges Parties to address climate change in a manner that will "allow ecosystems to adapt naturally to climate change". Through a resolution in October 1999, ICRI further encouraged the UNFCCC to address the coral bleaching phenomenon. In November 2000, the UNFCCC Conference of the Parties (COP-6) will consider actions to deal with the adverse effects of climate change, to facilitate transfer of technologies, and to develop capacity building programmes.

A concerted effort is needed to ensure that progress in these areas continues. Addressing global climate change requires national and individual commitments to altering current life styles that have led to worldwide changes. As members of the global community, we must speak out loudly in support of international efforts to reduce harmful emissions of greenhouse gases. Coral reef managers and scientists should submit frequent reports on coral bleaching to their local policymakers and to their Convention delegates, expressing ongoing concern for the effects of climate change on coral reefs and other ecosystems, and calling for continued attention to the problem in international forums.

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Raleigh International: www.raleigh.org.uk

Reef Base: www.cgiar.org/iclarm/resprg/reefbase/framet

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